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Construction Engineering
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2011 In-Water Testing of Aquatic Nuisance Species Dispersal Barriers IIA And IIB with Increased Voltage and Frequency Operating Parameters

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Jonathan C. Trovillion, Carey L. Baxter, Ethan T. Trovillion,
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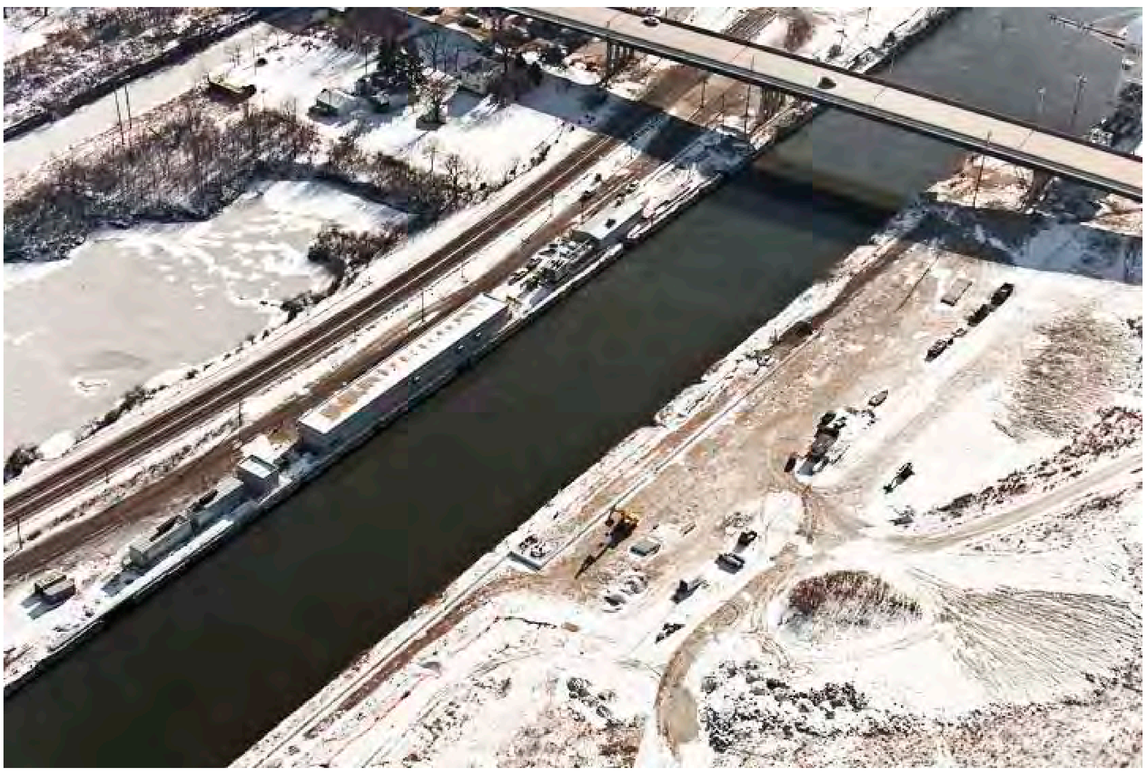

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Abstract: US Army Engineer District – Chicago operates an electric field-based aquatic nuisance species dispersal barrier system in the Chicago Sanitary and Ship Canal (CSSC), Romeoville, IL. The barriers were constructed to prevent the movement of invasive species, such as Asian bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*Hypophthalmichthys molitrix*) between the Mississippi River and Great Lakes basins. The objective of this project was to perform a series of in-water tests on the barrier addressing field-strength mapping, sparking potential during barge fleeting and collision, voltage potentials between barges traversing the barriers, personnel in-water shock potential, stray-current corrosion potential, and optimal settings for the parasitic barrier system. Test results and analysis indicate there is no significant risk of personnel shock hazard in the fleeting area during barrier operations for any operating configuration. Also, while some operational scenarios were found to increase sparking risk if barges collide with each other or separate metal objects, analysis indicates that concerns about coal dust explosion hazard from sparking are not supported by the technical literature. A detailed set of data, analysis, conclusions, and recommendations is provided in the report text and four appendices.

Executive Summary

In an ongoing effort to test and define the relative safety of the three invasive species dispersal barriers on the Chicago Sanitary and Ship Canal (CSSC) at Romeoville, IL, the Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL) and Chicago District performed in-water safety testing using various operational settings and configurations. The work was performed from 4 - 12 February and 12 - 16 June 2011. The seven objectives established for this testing effort: (1) map field strengths, (2) determine sparking potential during fleeting operations, (3) determine sparking potential in the event of a collision in the fleeting area, (4) measure voltage potential between barges traversing the canal over the barriers, (5) determine personnel shock potential at the bollards at the fleeting area, (6) determine corrosion potential, and (7) determine the optimal settings for the parasitic barrier system. Each objective was accomplished for six different target operational configurations: (A) IIA at 2.0 V/in., IIB at 2.3 V/in., (B) both IIA and IIB at 2.3 V/in., (C) both IIA and IIB at 2.0 V/in., (D) IIA alone at 2.3 V/in., (E) IIB alone at 2.0 V/in., and (F) IIB alone at 2.3 V/in. The measurements and observations recorded during these tests were compiled and analyzed to determine the in-water safety concerns associated with each of the various operational configurations.

The field strength testing and analysis indicated that larger areas of risk to a person-in-water are present when operating barriers IIA and IIB concurrently. However, only a small increase in the area of risk results with an increase of operational parameters from 2.0 V/in. to 2.3 V/in. Sparking was observed during fleeting operations, mainly during the insertion procedure when both barriers were in operation. No significant increase in risk of sparking was observed due to the increase in operations from 2.0 V/in. to 2.3 V/in. There is a significant increase in risk of sparking when a tow spanning both IIA and IIB with both operating (versus barrier IIA operating alone) collides with barge in fleeting area. The likelihood of sparking causing an explosion or fire at the coal-loading facility due to coal dust is negligible. Operation of the barriers does not adversely affect corrosion potential for in-water steel structures at Midwest Generation fleeting area. No risk of personal shock hazard was observed at the bollards in the fleeting area. Test results did not provide any clear evidence to refute that the

optimal parasitic electrode configuration is consistent with SRI recommendations that only two of the three parasitic structures are connected together such that they are the outermost structures adjacent to the active arrays.

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Preface

This study was conducted for the US Army Engineer District – Chicago under Project 114532, "CSSC Dispersal Barrier II, ERDC-CERL Safety Studies." The technical monitor was Charles B. Shea, CELRC-PM-PM.

The work was performed by the Materials and Structures Branch (CF-M) of the Facilities Division (CF), US Army Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL). At the time of publication, Vicki L. Van Blaricum was Chief, CEERD-CF-M; L. Michael Golish was Chief, CEERD-CF; and Martin J. Savoie was the Technical Director for Installations. The Deputy Director of ERDC-CERL was Dr. Kirankumar Topudurti and the Director was Dr. Ilker Adiguzel.

COL Kevin J. Wilson was the Commander and Executive Director of ERDC, and Dr. Jeffery P. Holland was the Director.

1 Introduction

1.1 Background

US Army Engineer District – Chicago is safely operating an electric field-based aquatic nuisance species dispersal barrier system in the Chicago Sanitary and Ship Canal (CSSC), Romeoville, IL. The barriers were constructed by Smith-Root, Inc., sole licensees of US patent 4,750,451[1], to prevent the movement of invasive species, such as Asian bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*Hypophthalmichthys molitrix*) [12], between the Mississippi River and Great Lakes basins. The barrier project consists of two distinct parts: the demonstration barrier (Barrier I) and Barrier II. Barrier I, which consists of steel cables fastened to concrete supports that rest on the bottom of the canal, sends a low-voltage, pulsing direct current (DC) through the water in order to repel invasive fish. Barrier II, also a pulsed DC apparatus, is located 800 to 1,300 ft downstream of Barrier I. Barrier II is able to generate a more powerful electric field over a larger area. It consists of two sets of electrical arrays and control houses, known as Barriers IIA and IIB. Each control house and set of arrays can be operated independently. Barrier IIA is operated during maintenance activities or as otherwise needed, and Barrier IIB is fully operational. Figure 1 shows the relative locations of Barriers I, IIA, and IIB.

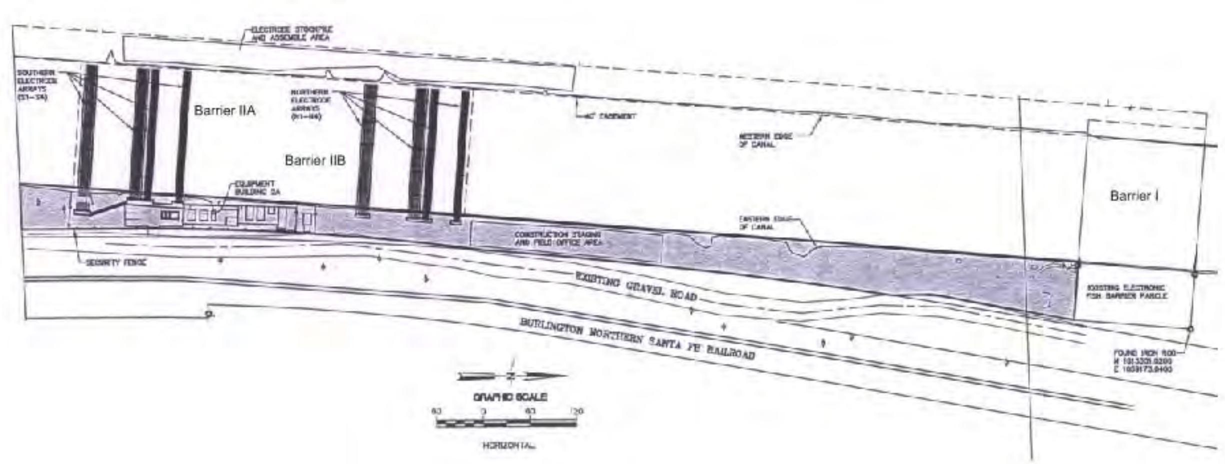

Figure 1. Relative locations of Barriers I, IIA, and IIB in the canal.

[1] Smith, David V. Fish repelling apparatus using a plurality of series connected pulse generators to produce an optimized electric field. United States Patent 4,750,451, issued 14 June 1988.

Before August 2009, Barriers I and IIA were operating at maximum in-water field strength at the water surface of 1 volt/inch (V/in.) with five pulses per second at a frequency of 5 hertz (Hz), and each pulse 4 milliseconds (ms) in duration. The US Army Corps of Engineers (USACE) and Smith-Root are engaged in an ongoing research program to identify the most effective combination of electric field strength, pulse frequency, and pulse duration for deterring all sizes of Asian carp. After environmental DNA (eDNA) monitoring indicated that Asian carp may have migrated closer to the barrier system than previously thought, the operating parameters at Barrier IIA were increased in August 2009 to levels recommended based on the research completed at that time: a maximum in-water field strength at the water surface of 2 V/in. with a pulse rate of 15 Hz and a pulse duration of 6.5 ms. The operating parameters at Barrier I were not changed because the equipment at Barrier I is not capable of operating at the higher recommended operating parameters.

Increasing the Barrier IIA operating parameters raised concerns about conducting barge and boat operations safely, and the potential hazards to a person who accidentally fell into the water while traversing the barriers. During preliminary discussions between ERDC-CERL[2], the Ninth US Coast Guard (USCG) District and Captain of Port Lake Michigan, and Chicago District, it was emphasized that it is crucial to identify and understand the risks associated with the new operating parameters. Additional tests were completed in August and September 2009 by teams from ERDC-CERL and Coast Guard Office of Design and Engineering Standards (CG 521) with Barrier IIA operating at 2 V/in., 15 Hz, and 6.5 ms pulse width. Test results were shared with the USCG that resulted in changes in the rules of navigation to allow the safe passage of barges carrying combustible or flammable liquid in bulk (i.e., red-flag barges) and recreational boats across the barriers.

Research into the optimal operating parameters to deter all sizes of Asian carp has continued. The latest research indicates that operating at a pulse rate of 30 Hz, pulse duration of 2.5 ms, and a maximum in-water field strength at the water surface of 2.3 V/in. may be most effective for deterring even small Asian carp. USACE is considering changing the Barrier II operating parameters to the latter. Testing for safety concerns in the waterway along with ground currents and electromagnetic radiation (EMR)

[2] Engineer Research and Development Center - Construction Engineering Research Laboratory, Champaign, IL.

in the air were conducted in February 2011 to determine the effects of these new operational parameters. The results of the in-water testing are included in this report; safety testing results for ground currents and EMR will be documented in a separate report. The results of the safety testing will be a key element in recommendations about optimum operating parameters.

Barrier IIB has been operational since April 2011, and has undergone testing that verified it can perform at the specified parameters. Also, new parasitic structures have since been installed in the canal as part of Barrier IIB construction. These structures, typically referred to as “parasitics” in this report, are electrode arrays configured as steel grids and mounted to concrete curbs that rest on the bottom of the canal. These are located down-canal from Barrier IIA, up-canal from Barrier IIB, and between IIA and IIB. They collect the stray currents on one side of a barrier and, via an electrical bus on shore, provide a low-impedance path for those currents to return to other side of barrier.

The southernmost parasitic grid is designated as 1; the middle grid as 2; and the northernmost grid as 3. Each grid is connected to the electrical bus on the western shore by metal cables that are welded to the grid structure. There are several switches that allow each parasitic to be connected to and disconnected from the bus. By closing each switch (i.e., setting it to the *on* position), the parasitics are connected to each other via bus. By opening a switch (i.e., setting it to the *off* position), a parasitic may be disconnected from the bus. The positioning of these switches is presented throughout the report.

The in-water testing was undertaken to evaluate the effects of changing the barrier operating parameters, including operation of the parasitics on the safe operation of Barrier IIB.

1.2 Objective

The objective of this project was to support the Chicago District by performing a series of tests on the barrier to:

1. map and quantify the voltage gradient and current potential across Barrier I, Barrier IIA, and Barrier IIB in order to evaluate the voltages and currents a person would be subjected to while in the water in the barrier area

2. quantify and evaluate the potential for sparking during fleeting operations at the Midwest Generation, LLC, power facility fleeting area
3. quantify and evaluate the possibility of sparking between fixed barges at the fleeting area and a moving long tow that is traveling south over Barrier IIA and Barrier IIB while contacting a moored barge in the fleeting area
4. quantify the voltage potential between barges in a long tow while passing over Barrier I, Barrier IIB and Barrier IIA
5. assess the potential shock hazard between the fleeting area dock bollards and a fixed barge
6. assess the corrosion potential of in-water steel structures in the fleeting area
7. determine the most effective method for operating the parasitic system.

1.3 Approach

Barrier IIA and IIB were adjusted to operate according to each of the testing objectives outlined above. The operational parameters were verified, and actual values were recorded during testing. Environmental data such as ambient temperature, humidity, and water conductivity were recorded throughout all testing.

The watercraft used for field mapping was a 22 ft fiberglass-hull Guardian Boston Whaler owned by USACE. The sparking potential, corrosion potential, and long-tow tests were performed with towboats and barges provided by commercial material-transfer companies.

The main text of this report includes summary tables, most of which are derived from the raw test data. The unabridged tables of raw data are presented separately, in Chapter 4, for more detailed examination.

Details on the instrumentation used for data collection and the data reduction procedures are presented in Appendix A.

2 Experiments

Tests were completed for the pulser target operational configurations listed in Summary Table A. Throughout all testing, environmental data such as ambient temperature, humidity, and water conductivity were recorded. The unabridged data are presented in Chapter 4, Table 1.

Summary Table A. Target operational scenarios.

	Barrier IIA	Barrier IIB	Barrier I
A (Alpha)*	2.0 V/in., 15 Hz, 6.5 ms	2.3 V/in., 30 Hz, 2.5 ms	1 V/in., 5 Hz, 4 ms
B (Bravo)*	2.3 V/in., 30 Hz, 2.5 ms	2.3 V/in., 30 Hz, 2.5 ms	1 V/in., 5 Hz, 4 ms
C (Charlie)*	2.0 V/in., 15 Hz, 6.5 ms	2.0 V/in., 15 Hz, 6.5 ms	1 V/in., 5 Hz, 4 ms
D (Delta)*	2.3 V/in., 30 Hz, 2.5 ms	OFF	1 V/in., 5 Hz, 4 ms
E (Echo)*	OFF	2.3 V/in., 30 Hz, 2.5 ms	1 V/in., 5 Hz, 4 ms
F (Foxtrot)*	OFF	2.0 V/in., 15 Hz, 6.5 ms	1 V/in., 5 Hz, 4 ms

* Actual test field strengths approximate.

2.1 Field mapping (Objective 1)

2.1.1 Procedure

Field mapping was conducted for each of the six operational scenarios. Measurements of voltage (1) between horizontal electrodes spaced 1 – 6 ft apart were used to map the horizontal electric field, and (2) between two vertical electrodes spaced 5 ft apart were used to map the vertical field. Measurements of current (1) through a 100-ohm (Ω) resistor between two horizontal electrodes spaced 1 ft apart was used to simulate current flow through the chest, (2) through a 500 Ω resistor between two horizontal electrodes spaced 6 ft apart was used to simulate current flow through a body floating prone in the canal, and (3) through a 500 Ω resistor between two vertical electrodes spaced 5 ft apart was used to simulate current flow through an upright body. A schematic of the testing apparatus is shown in Figure 2.

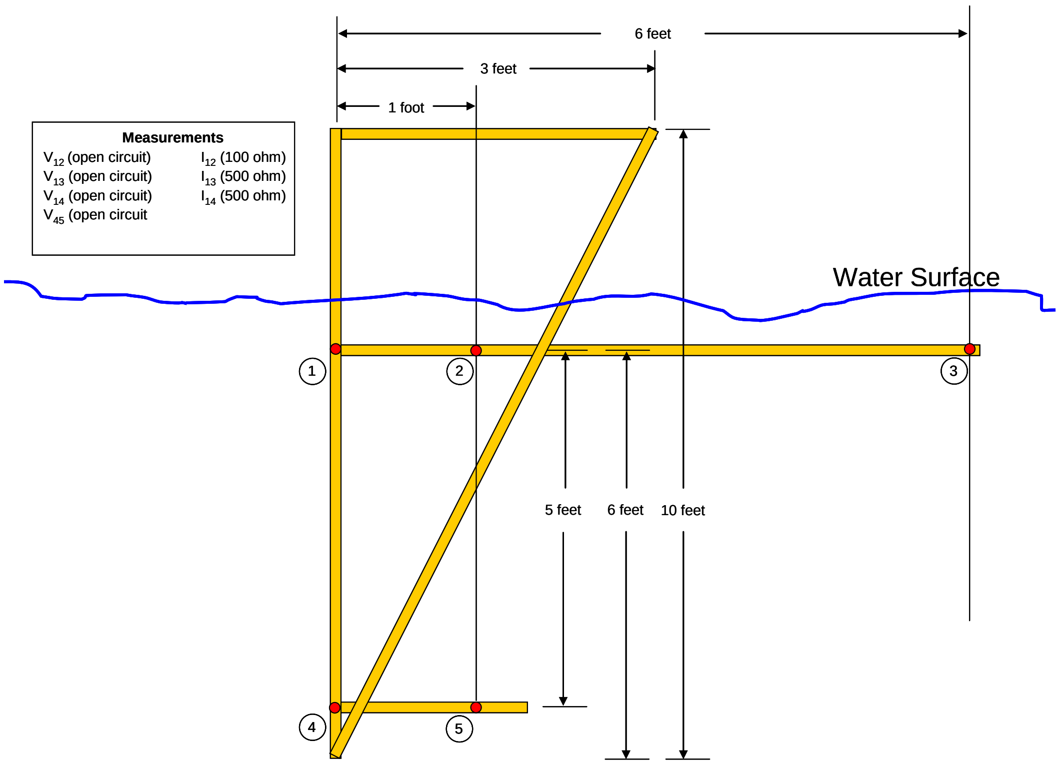

Figure 2. Electrode array for voltage gradient and current mapping.

Data were continuously collected as the boat traversed the barriers from south of the fleeting area to north of the pipeline arch. (See section 2.4.1 for layout illustrations.) This extends the data-collection region well beyond Barrier I to the north and Barrier IIA to the south.

Geopositional data were taken concurrently with the voltage and current measurements during field mapping to allow them to be georeferenced. A minimum of six passes — two along the center of the canal, two along the east wall, and two along the west wall — were taken at each of the pulser configurations shown in Summary Table A.

2.1.2 Analysis

Field mapping data were used to determine voltages and currents a person would be subjected to while in the water in the barrier area. The critical threshold voltage levels published in a Navy Experimental Diving Unit (NEDU) report [6] were used as the basis for computing the range of harmful physiological effects that would result from the measured values. The NEDU based its threshold voltage levels for harmful effects on International Electrotechnical Commission (IEC) Publication 60479-1, *Effects of Current on Human Beings and Livestock - Part 1: General Aspects* [11].

Table 13 in IEC Publication 60479-1, reproduced in Appendix B of this report as Table B1, defines four zones of physiological effects to the human body due to DC pulses. The zones are differentiated by duration of current pulse and body current. The most harmful effects occur in Zone DC-4; these include cardiac arrest, breathing arrest, and burns or other cellular damage.

The NEDU computation [6] is for the worst-case effect: current through the chest of a body upright over the barrier. For this scenario, the measurements of the open-circuit voltage with 1 ft electrode spacing at approximately 1 ft below the surface (referred to as V12) are used.[3] Minimum electric field strengths required to induce physiological effects were derived using the formulas and methods given in [6]. Details of the analysis are presented in Appendix B and summarized in Table B3. A worst-case value of 0.05 V/in. was determined to be the threshold for ventricular fibrillation. Worst-case values of 0.03 V/in. (for pulse width 2.5 ms) and 0.02 V/in. (for pulse width 6.5 ms) were determined to be the threshold for involuntary muscular contractions. The geographic limit values were obtained for each run by examining the electric field plots and estimating where the voltages crossed the threshold limit lines.

The actual field strength measured during this testing may be seen in the figures presented in Appendix C. Actual field strength sometimes exceeded the target operational configurations for these tests. In an effort to determine the impact of these higher values, sensitivity analysis was conducted (see Appendix B). Mapping runs which had at least one range of harmful effect values corresponding to one of the two greatest-extent values (one north of the barriers and one south) were selected from configuration Bravo. The entire dataset from these runs was scaled by +/- 20%. The change in the extent of the safety zones (+/- 0.05 V/in. man-overboard criteria) north and south of barriers IIA and IIB was then reevaluated using the scaled datasets.

2.1.3 Results and observations

Pulser and parasitic configurations along with the approximate run times are listed in Table 2 (see Chapter 4). Electrical field strength data for V12

[3] Although five voltages and three currents were measured, only the V12 measurement is needed to perform the analysis in this report. The other voltage and current measurements were made for future analyses.

are presented in Appendices C and D. The zero point on the x-axis of these figures is centered on Barrier IIB's narrow array (see Figure C1). This is where the electric field strength of Barrier IIB is the strongest.

Peak voltage potential was measured. No filtering was applied to some of the images, such as run 16 on February 11 and run 4 on February 12, so background noise is evident in some cases. This noise is caused by radio interference from nearby transmitters and 60 Hz (and harmonic) stray electrical currents originating from the Midwest Generation electric power station. To improve graphical presentation, filtering was applied to some of the data in order to remove noise and clutter when it obscured the useful data. Peak voltages are not affected by the filtering.

No geo-tracking data were available for run 18 on February 11 and runs 17 and 18 on February 12 due to periodic changes in the GPS satellite constellation, which prevented adequate carrier phase lock to determine geopositional data through direct observation. Geo-referencing was accomplished by estimating the speed of the boat based on the travel time between IIA and IIB and between IIB and I. Because the geo tracks were interpolated, these runs were not used in the analysis of harmful effects.

The electric field dataset for run 16 on June 14 was incomplete. The data recorder stopped prematurely. Therefore, this run also was not used in the harmful-effects analysis.

The derivation of the hazardous electrical field levels and the procedure for finding the range of likely harmful effects are presented in Appendix B.

Table 3 and Table 4 (see Chapter 4) present the range of voltage gradients sufficient to cause harmful physiological effects for each run completed over each barrier. The greatest range of effect is shown in Summary Table B. The worst case (maximum extent) occurred, as expected, for pulser configuration B with all parasitics off. The best case (minimum extent) occurred, as expected, for pulser configuration D when Barrier IIB was not operating and parasitic 1 and 2 on. The best case with both Barrier IIA and IIB operating occurred for pulser configuration B with all parasitics on.

One would expect that the ranges of greatest extent for configurations E and F of Barriers IIA and IIB would be nearly the same as for configuration D. In all three cases, only one pulser is operating — pulser IIA for configuration D and IIB for configurations E and F. It is thought that the parasitic settings affect the measured field strengths and, consequently, the ranges of physiological effects. In configuration D, parasitics 1 and 2 are on, both of which are directly adjacent to the Barrier IIA arrays. In configurations E and F, parasitics 1 and 3 are on. Parasitic 3 is directly adjacent to the Barrier IIB arrays, but parasitic 1 is not. Parasitic 1 is on the downstream side of Barrier IIA (as shown in Chapter 4, Figure 3) Pulser current from Barrier IIB is being directed from parasitic 3 to parasitic 1, raising the electrical field levels upstream from parasitic 1. Thus the field strength increases between parasitic 1 and 3, as reflected in configuration A, B, and C data. If parasitics 2 and 3 had been on in pulser configurations E and F, the range of greatest extent would be confined to the region immediately adjacent to Barrier IIB, as it is confined to the region immediately adjacent to Barrier IIA for configuration D with parasitics 1 and 2 on. In June, it was not possible to test with parasitics 2 and 3 on for configurations E and F due to electrical/mechanical problems with parasitic 2. Once parasitic 2 is repaired, mapping should be repeated with only parasitics 2 and 3 on.

The results of the sensitivity analysis (see Appendix B) show that the 20% increase or decrease in the voltage amplitude will result in a 10% increase or decrease in the extent of the safety zones associated with ventricular fibrillation north and south of barriers IIA and IIB. The 10% change equates to an increase or decrease of 120 ft (36 m) in the extent of the safety zone based on the 0.05 V/in. man-overboard criteria.

Summary Table B. Range of greatest extent of voltage gradients (≥0.05 V/in.) sufficient to cause harmful physiological effects (see Table 3 and Table 4, Chapter 4).

Pulser Configuration	Parasitic Settings			Range of Greatest Extent					
	1	2	3	Barriers IIA and IIB, in ft (m)			Barrier I, in ft (m)		
				≥ 0.05 V/in (ventricular fibrillation)	≥ 0.03 V/in (involuntary muscular reactions)	≥ 0.02 V/in (involuntary muscular reactions)	≥ 0.05 V/in (ventricular fibrillation)	≥ 0.03 V/in (involuntary muscular reactions)	≥ 0.02 V/in (involuntary muscular reactions)
A (Feb 12)	On	Off	On	1,231 (375)	2,083 (635)*	1707 (520)	263 (80)	2149 (655)*	N/A
B (Feb 11)	Off	Off	Off	1,394 (425)	2,083 (635)*	N/A	296 (90)	2,083 (635)*	N/A
B (Feb 11)	On	Off	On	1,197 (365)	2,100 (640)*	N/A	296 (90)	2,100 (640)*	N/A
B (Feb 11)	On	On	On	1,131 (345)	1,411 (430)	N/A	263 (80)	607 (185)	N/A
C (Feb 12)	On	Off	On	1,165 (355)	N/A	1658 (505)	263 (80)	2149 (655)*	N/A

Pulser Configuration	Parasitic Settings			Range of Greatest Extent					
	1	2	3	Barriers IIA and IIB, in ft (m)			Barrier I, in ft (m)		
				≥ 0.05 V/in (ventricular fibrillation)	≥ 0.03 V/in (involuntary muscular reactions)	≥ 0.02 V/in (involuntary muscular reactions)	≥ 0.05 V/in (ventricular fibrillation)	≥ 0.03 V/in (involuntary muscular reactions)	≥ 0.02 V/in (involuntary muscular reactions)
D (Feb 12)	On	On	Off	607 (185)	804 (245)	N/A	247 (75)	542 (165)	N/A
E (June 14)	On	Off	On	1050 (320)	1181 (360)	N/A	295 (90)	492 (150)	N/A
F (June 14)	On	Off	On	1001 (305)	1132 (345)	1296 (395)	344 (105)	525 (160)	N/A

* Range of harmful effects extends from south of Barrier IIA to north of Barrier I, there is no safe zone between barriers.

2.1.4 Conclusions

Figure 3 shows the areas of likely harmful effects for the six pulser configurations given in Chapter 4, Table 5. Areas associated with involuntary muscular contraction (yellow) are larger than those associated with ventricular fibrillation (red) due to lower threshold voltage values (Appendix B).

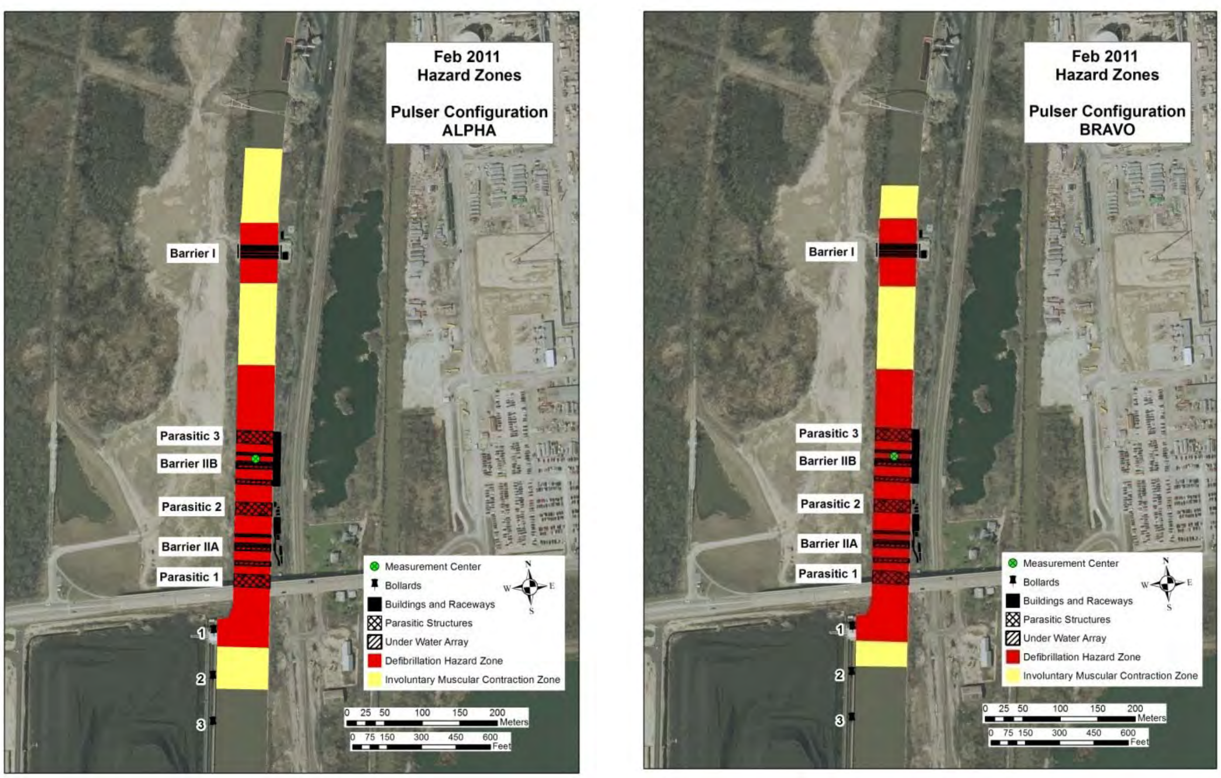

Figure 3. Relative locations of areas of likely harmful effects for the four pulser configurations of Table 5 (continued to next page).

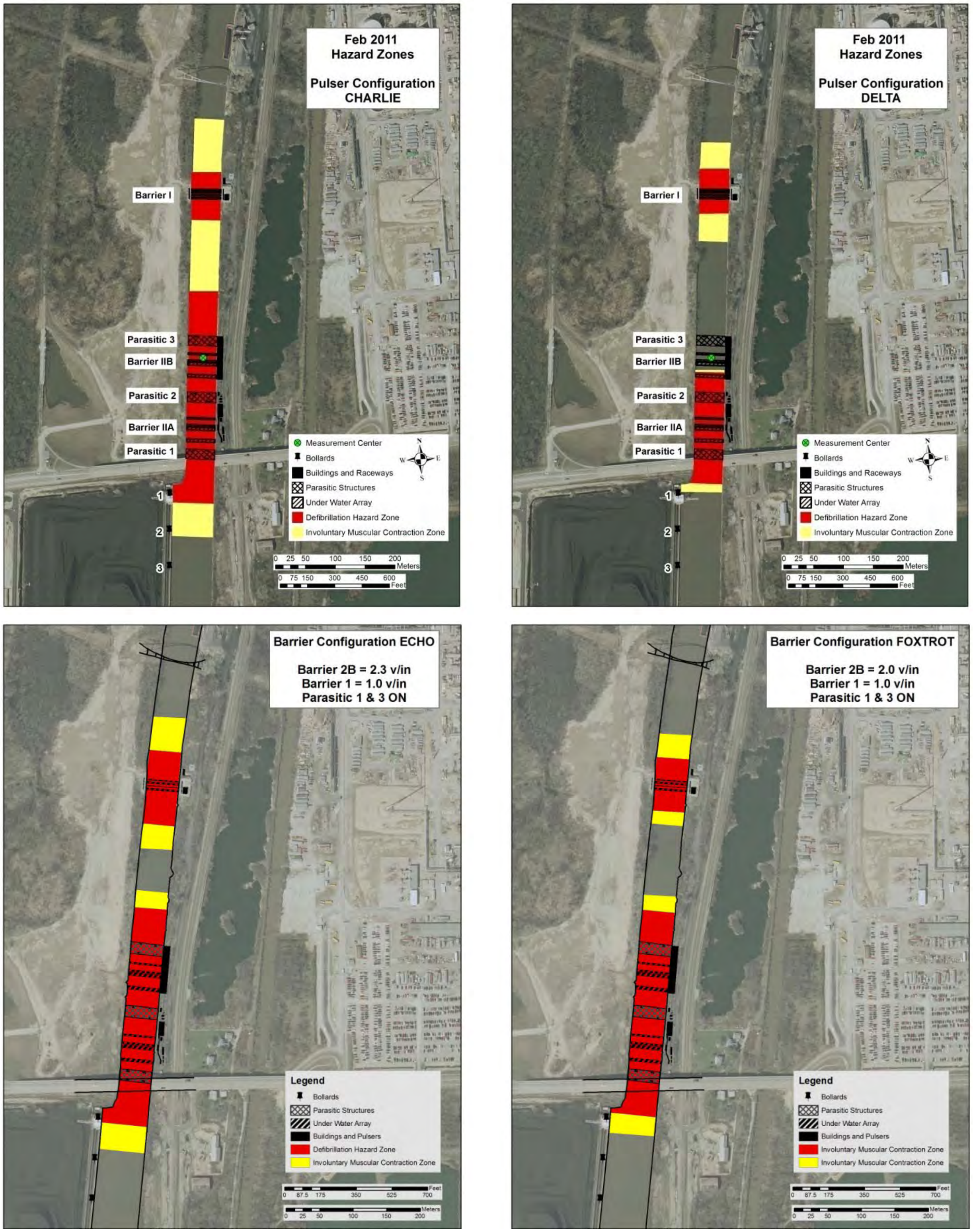

Figure 3 (concluded).

The six areas associated with ventricular fibrillation have been combined into Figure 4.The threshold values derived for pulser configurations Alpha, Charlie, and Foxtrot are lower (≥ 0.02 V/in.) than pulser configurations Bravo, Delta, and Echo (≥ 0.03 V/in.) due to the longer pulse width as it was incorporated in the calculations. These six areas are shown with the harmful effect zone from 2009, when Barrier IIA was operating alone at 2.0 V/in. The results of the sensitivity analysis suggest that these areas represent worst-case estimates of the actual hazard zones.

For pulser configurations E and F, the harmful-effect zones are similar to configurations A, B, and C because field mapping was conducted with only parasitics 1 and 3 on. Electrical/mechanical problems with parasitic 2 prevented it from being used in the mapping. Once parasitic 2 is repaired, mapping should be repeated with only parasitics 2 and 3 on.

If the operating parameters of a barrier are changed, then the electric field strengths in the water must be mapped again to determine the areas of harmful effects. However, the approach laid out in Appendix B would still be applicable and can be used to evaluate the new field mapping results.

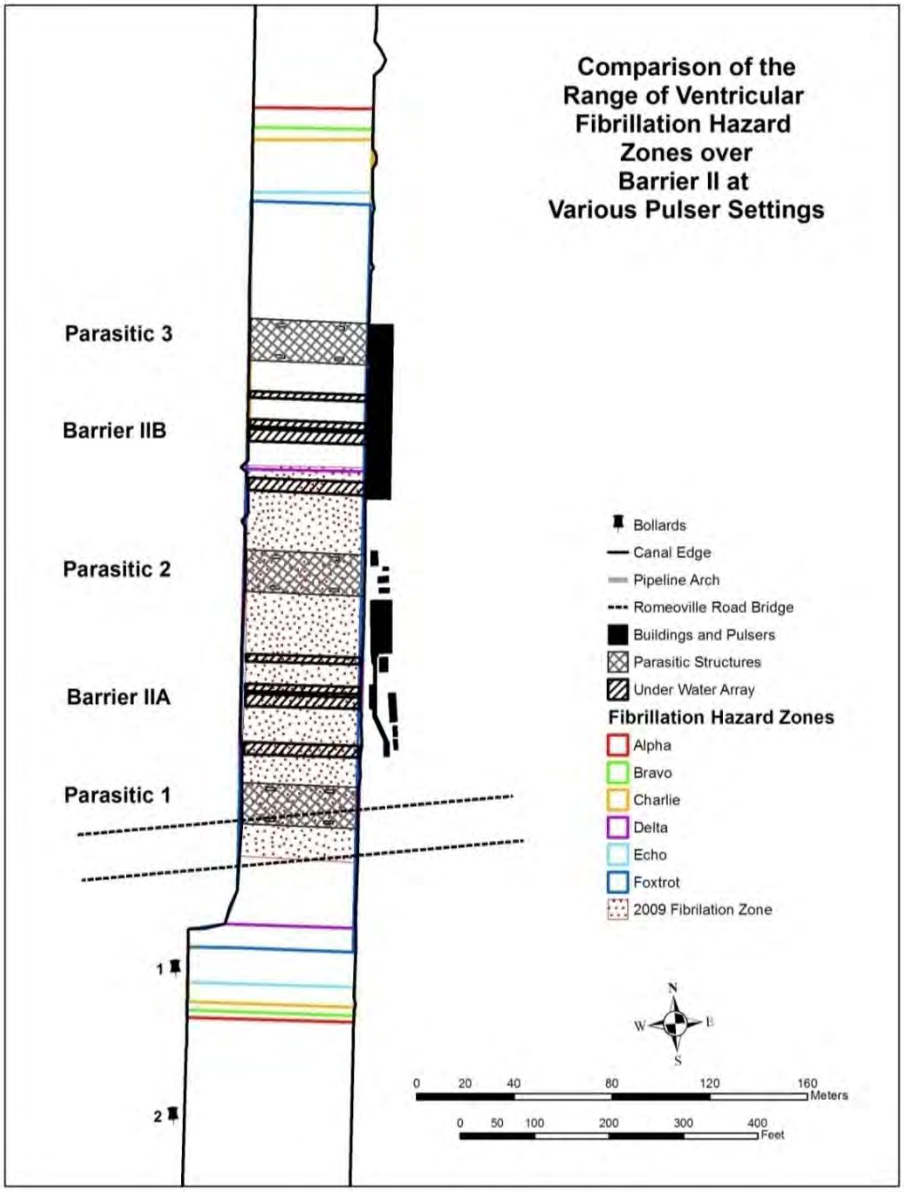

Figure 4. Locations of likely harmful effects for the six pulser configurations in Table 5, Chapter 4.

2.2 Sparking potential testing at fleeting area (Objectives 2 and 3)

2.2.1 Procedure

Sparking potential testing was completed for each of four operational scenarios. Three configurations for assembling a tow were utilized for testing sparking potential during fleeting operations: assembling a tow with the barges in *series* (Figure 5 and Figure 6), in *parallel* (Figure 7 and Figure 8), and *insertion* of a single barge into a tow (Figure 9 and Figure 10).

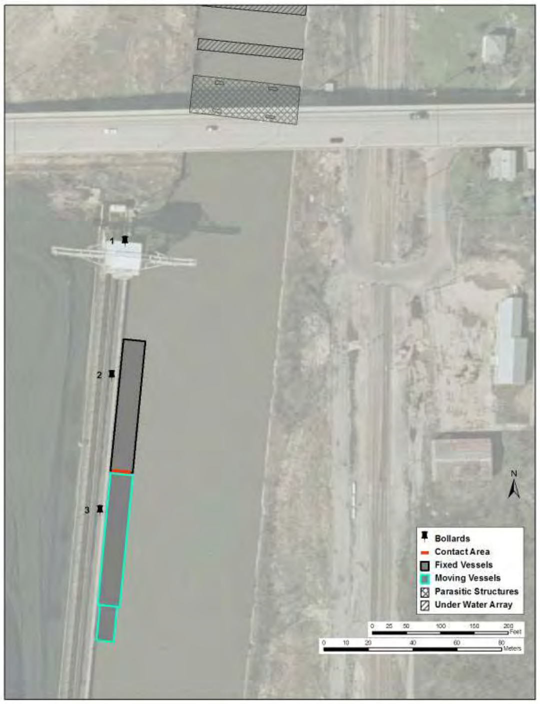

Figure 5. Sparking potential testing scenario for a tow with barges in series, 5 February 2011.

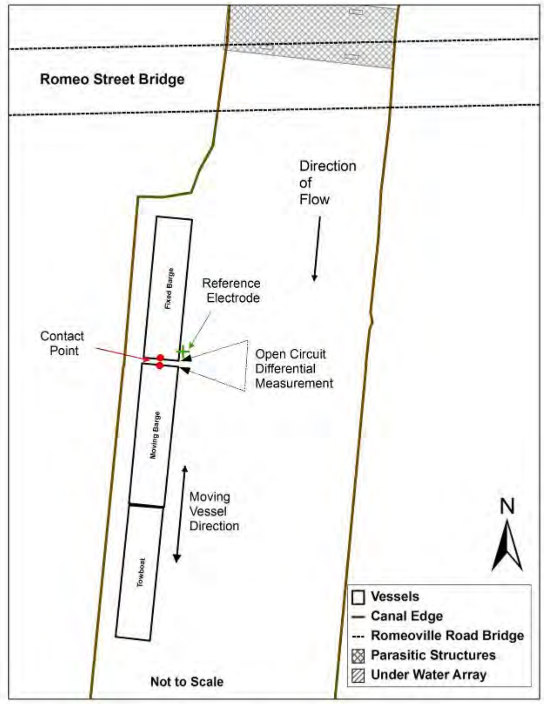

Figure 6. Instrumentation for testing of a tow with barges in series.

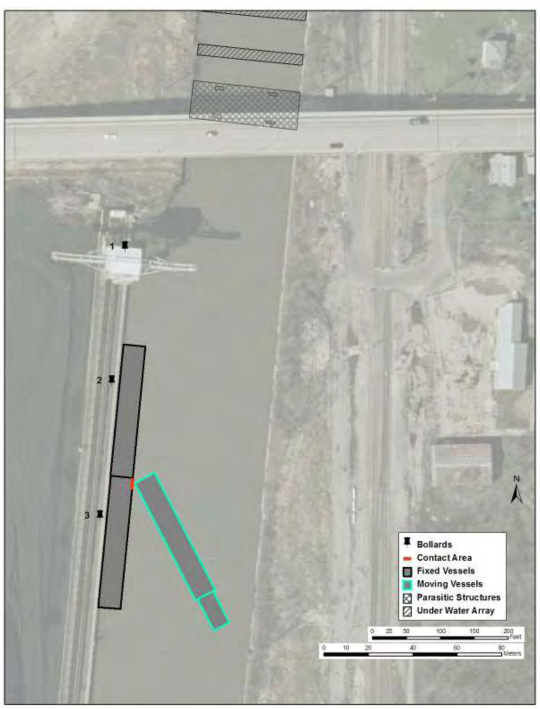

Figure 7. Sparking potential testing scenario for a tow with barges in parallel, 5 February 2011.

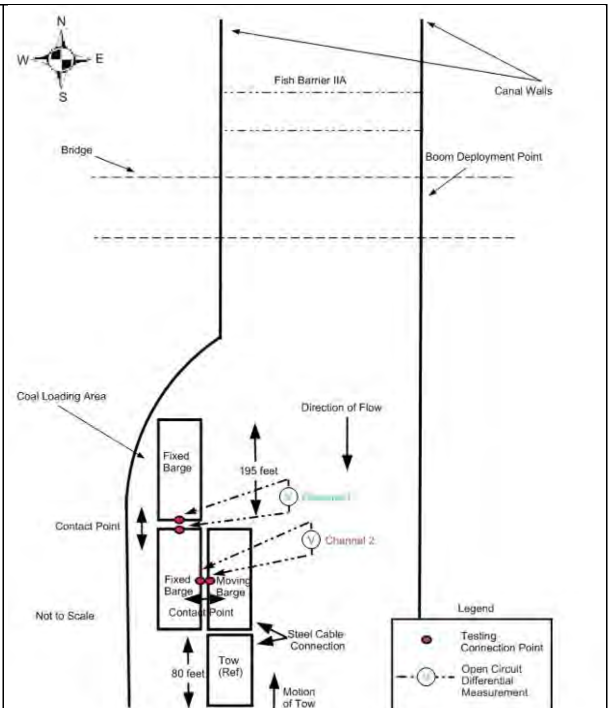

Figure 8. Instrumentation for testing of assembling a tow with barges in parallel.

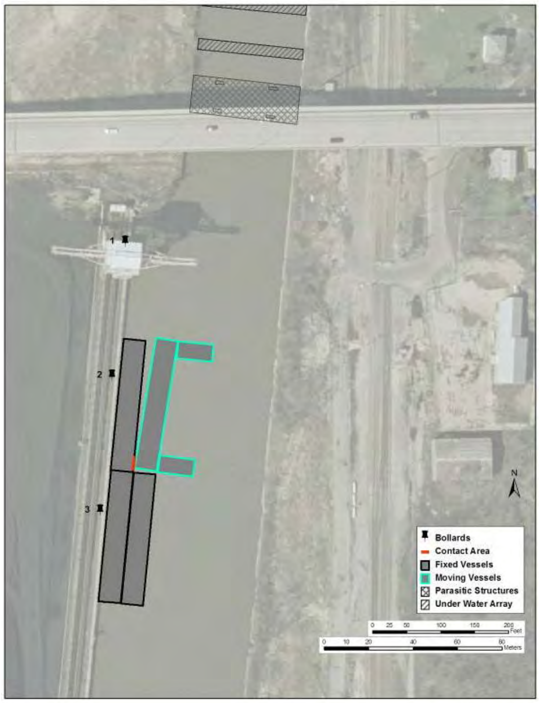

Figure 9. Sparking potential testing scenario for inserting a barge into a tow on 5 February 2011.

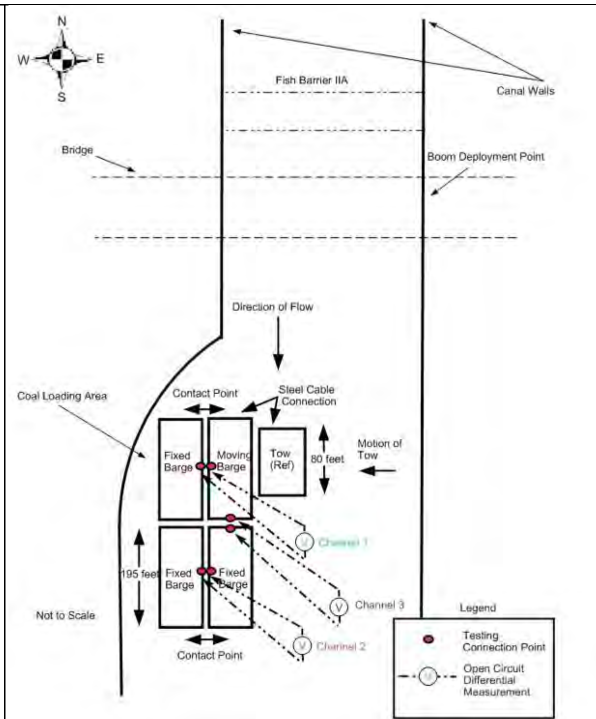

Figure 10. Instrumentation for testing of inserting a barge into a tow.

A fourth test simulated the collision of a tow consisting of five barges in series with two towboats (one on each end of the tow) spanning both Barriers IIA and IIB with two parallel barges moored in the fleeting area. The tow passed over the electrode arrays of Barrier IIA and Barrier IIB while approaching the fleeting area (Figure 11 and Figure 12).

In all cases, barge fleeting occurred at the Midwest Generation fleeting area at bollard 2 and southward. The following measurements and observations were recorded:

1. the open-circuit voltage potential between moored and moving barge as the tow approached and touched three times
2. the electric current flowing between moored and moving barges as the tow approached and touched three times.
3. observations of whether sparking occurred while the moving barge made and broke contact with the fixed barge three times.

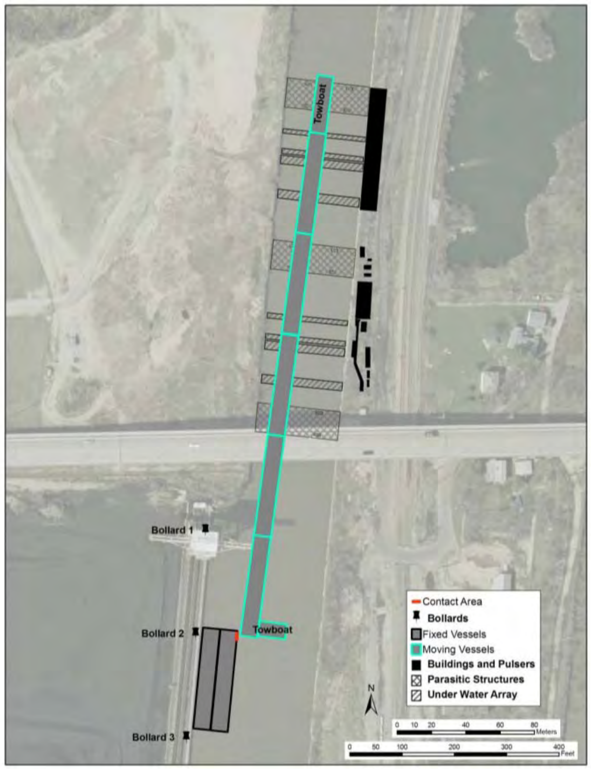

Figure 11. A tow over Barriers IIA and IIB contacting a moored barge in the fleeting area on 7 February 2011.

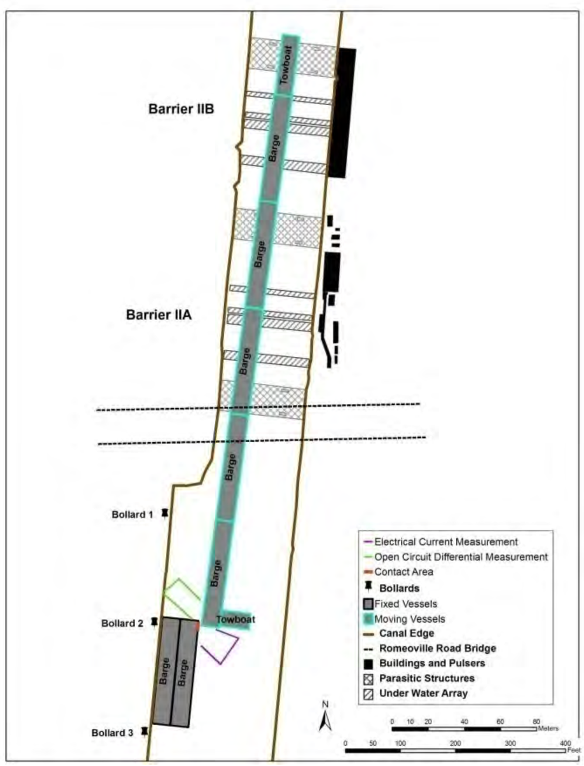

Figure 12. Electrical measurements between a tow over Barriers IIA and IIB and a barge moored in the fleeting area.

Sparking occurs when barges contact and separate. Therefore, for each tow configuration, the moving tow was positioned in close proximity to the moored barge that it made contact with. The contact points are shown on Figure 5, Figure 7, Figure 9, and Figure 11. The tow initially made contact with the moored barge and then slowly scraped the moored barge as it moved away. This was repeated at least three times. Key personnel were positioned to look for sparking during each contact and separation for each test. Voltages and currents between the fixed barges and the moving tow were alternately measured throughout this process. The measurement locations are shown on Figure 6, Figure 8, Figure 10 and Figure 12.

All barges used in the testing were fully loaded to achieve maximum underwater hull exposure. The moored barges for each sparking potential scenario were connected to the dock with soft line and to each other with wire rope. The steel barge-hulls were in contact with the wooden bumpers on the concrete dock walls providing a highly resistive ground path. The tow boat and moving barge were connected with wire rope. This mooring configuration—soft lines to shore and wire rope between barges and barges to tow boat—was consistent throughout testing.

2.2.2 Analysis

The percentage of sparking events for each pulser configuration was computed and peak voltages and currents at the time just before a bumping / collision event were visually estimated from plots of the data.

Rudimentary analyses of the electrical characteristics of a sparking event were performed using the voltage and current data. Voltage, or electric potential, is the amount of energy available to perform work on an individual charge. It is the energy per unit charge. The current is the rate at which the charges are moving. In the case of a steel barge hull, the charges are electrons.

From the voltage and current data, a rough estimate of the amount of energy in each pulse may be calculated using the formula

$$E = V \times I \times t_{\mathrm{p}}$$

where

E = energy (joules)

V = voltage (volts)
I = current (amps)
t_p = time (pulse length in seconds).

This estimation method is analogous to the way energy use is recorded by a common residential electric meter. The value of t_p for each pulser configuration is listed in Table 5. Note that for the same voltage and current, longer pulses have more energy. The average voltage and current for each pulser configuration and parasitic setting were used for the energy computation.

2.2.3 Results and observations

Data for the sparking potential tests during fleeting operations are listed in Table 6, and data for the sparking potential tests during simulated collision are listed in Table 7. Sparking observers consisted of representatives from the test team at ERDC-CERL, one representative from Chicago District, one representative from the Coast Guard Marine Safety Unit, and barge crewmen.

During fleeting operations testing, an observer saw sparking on 1.9% (1/52) of the series (fore and aft) mooring tests, on 0% (0/49) of the parallel mooring tests, on 38% (18/ 48) of the insertion tests. During the collision tests, observers saw sparking on 100% (36/36) of the tests when barriers II A and II B were operating, on 100% (8/8) when only IIB was operating, and none 0% (0/6) when only Barrier IIA was operating. During the collision tests, significant voltages and currents were measured (see Table 7). In summary, sparking was observed during operational scenarios A, B, C, E, and F but never during D when only Barrier IIA was in operation.

Summary Table C compiles the basic sparking observation results during simulated fleeting operations in the fleeting area. There is little difference in the frequency of observed sparking between pulser configurations A, B, and C and the state of the parasitics; however configurations E and F had the lowest frequencies. Sparking was observed most frequently during the insertion process.

Summary Table C. Summary of sparking observations based on test results for sparking potential during fleeting operations (see Table 6, Chapter 4).

Pulser Configuration	Parasitic Settings			# Sparking Observations / # barge contacts		
	1	2	3	Series	Parallel	Insertion
A (Feb 5)	On	On	On	0/6	0/6	4/6
A (Feb 5)	On	Off	On	0/6	0/7	1/6
B (Feb 5)	On	On	On	0/6	0/6	4/6
B (Feb 5)	On	Off	On	0/6	0/6	2/6
C (Feb 5)	On	On	On	0/6	0/6	3/6
C (Feb 5)	On	Off	On	0/6	0/6	4/6
D (Feb 5)	On	On	Off	1/6	0/6	0/7
E (June 15)	On	Off	On	0/4	0/2	0/2
F (June 15)	On	Off	On	0/6	0/4	0/2

Voltage values where sparking was observed ranged from 4.7 – 10 volts, while the values where no sparking was observed ranged from 1.0 – 9.9 volts. Similarly, the current values during sparking were in the same range as values measured where no sparking was observed.

Summary Table D compiles the voltage, current and estimated energy results for the simulated fleeting operations, based on the data presented in Chapter 4, Table 6. Note the consistently lower energy, throughout all barge and pulser configurations, when parasitics 1, 2, 3 were all on. The average reduction was 46% and the maximum was 75%.

Summary Table D. Summary of estimated energy based on results for sparking potential during fleeting operations (see Table 6, Chapter 4).

Barge Configuration	Pulser Configuration	Parasitic Settings			Average Peak voltage (volts)	Average Peak Short Circuit Current (Amps)	Estimated Energy (mJoules)
		1	2	3			
Series	A (Feb 5)	On	On	On	6.5	1.1	44.8
Series	A (Feb 5)	On	Off	On	6.6	1.5	62.6
Series	B (Feb 5)	On	On	On	7.2	0.9	17.0
Series	B (Feb 5)	On	Off	On	8.4	1.6	33.5
Series	C (Feb 5)	On	On	On	6.0	0.8	29.5
Series	C (Feb 5)	On	Off	On	8.2	1.5	81.7

Barge Configuration	Pulser Configuration	Parasitic Settings			Average Peak voltage (volts)	Average Peak Short Circuit Current (Amps)	Estimated Energy (mJoules)
		1	2	3			
Series	D (Feb 5)	On	On	Off	4.4	0.3	2.9
Series	E (June 15)	On	Off	On	2.0	0.3	1.3
Series	F (June 15)	On	Off	On	1.2	0.2	1.6
Parallel	A (Feb 5)	On	On	On	2.3	0.3	4.7
Parallel	A (Feb 5)	On	Off	On	3.2	0.4	8.0
Parallel	B (Feb 5)	On	On	On	2.5	0.3	1.8
Parallel	B (Feb 5)	On	Off	On	2.5	0.4	2.6
Parallel	C (Feb 5)	On	On	On	2.6	0.4	6.6
Parallel	C (Feb 5)	On	Off	On	2.8	0.6	11.0
Parallel	D (Feb 5)	On	On	Off	1.6	0.2	0.7
Parallel	E (June 15)	On	Off	On	0. 6	0.1	0.2
Parallel	F (June 15)	On	Off	On	0.5	0.1	0.3
Insertion	A (Feb 5)	On	On	On	6.7	1.0	43.3
Insertion	A (Feb 5)	On	Off	On	6.9	1.7	75.9
Insertion	B (Feb 5)	On	On	On	6.3	1.3	20.7
Insertion	B (Feb 5)	On	Off	On	8.6	1.7	35.5
Insertion	C (Feb 5)	On	On	On	5.5	1.0	34.4
Insertion	C (Feb 5)	On	Off	On	8.2	2.5	132.0
Insertion	D (Feb 5)	On	On	Off	1.6	0.2	0.9
Insertion	E (June 15)	On	Off	On	1.5	0.2	0.8
Insertion	F (June 15)	On	Off	On	1.3	0.2	1.7

The range of peak voltage measured for each operational configuration with all three parasitics in the on position was not significantly different than the ranges measured with only two of the parasitics connected. The estimated energy was consistently lower with all three parasitics in the on position in comparison to estimates with only two of the parasitic connected.

The collision tests (Table 7, with results compiled in Summary Table E) showed a range of peak voltages during sparking from 35.0 – 96.6 volts, in comparison to 15.3 – 19.2 volts when no sparking was observed. However, it should be noted that sparking was observed in every test of pulser configurations A, B, C, E, and F, but not during scenario D. No such range difference was observed in the electric current measurements.

Summary Table E. Test results for sparking potential during collision simulations, conducted on 7 February 2011 (see Table 7, Chapter 4).

Pulser Configuration	Parasitic Settings			Sparking Observations	Peak Voltage	Estimated Energy
	1	2	3			
A (Feb 7)	On	On	On	6/6	68.6 V – 78.4 V	5,667 mJ
A (Feb 7)	On	Off	On	6/6	60.3 V – 69.3 V	5,207 mJ
B (Feb 7)	On	On	On	6/6	67.4 V – 72.7 V	1,973 mJ
B (Feb 7)	On	Off	On	6/6	60.7 V – 72.6 V	1,941 mJ
C (Feb 7)	On	On	On	6/6	85.9 V – 96.3 V	12,033 mJ
C (Feb 7)	On	Off	On	6/6	19.8 V – 96.6 V	11,121 mJ
D (Feb 7)	On	On	Off	0/6	15.3 V – 19.2 V	727 mJ
E (June 15)	On	Off	On	4/4	35.0 – 62.0 V	2,774 mJ
F (June 15)	On	Off	On	4/4	68.0 – 72.0 V	2,581 mJ

During collision tests there was not a significant difference in the estimated energy between parasitic settings for each pulser configuration. This result was due to the tow spanning both barriers and all parasitics.

Sparking is caused by the separation of barges. When barges are positioned parallel with the stray current from the barriers, maximum potential difference between them may be observed. However, when barges are perpendicular to current, minimum potential difference and minimum current flow will be seen.

A limited literature review was conducted on the topic of electrical sparking. The US Occupational Safety and Health Administration (OSHA) has published several documents that discuss sparking, mostly related to machinery and protecting personnel from burns. OSHA has a web page about safety for the electric power generation, transmission, and distribution industry.[4] The review identified one document pertaining to explosion hazards in the coal industry, including coal-fired power plants [10]. This document suggests that the primary danger is from coal dust in a confined space. Concerning coal storage outside, the author states that

4 http://www.osha.gov/SLTC/powergeneration/index.html

> The raw coal for a pulverized fuel system is usually received from a variety of sources and the size is generally limited to approximately 2 inches or smaller. This raw coal is typically stored on an outside stockpile where it is moved around by frontend loaders. The fire and explosion hazards associated with this stockpile are usually limited to spontaneous combustion [10].

Further information on the potential ignition of coal dust from an electrical spark was provided through an examination of the Midwest Generation facility electrical safety provisions. Coordination with Midwest Generation environmental and electrical specialists provided information on the classification of various areas of the facility.

National Fire Protection Association (NFPA) Code 70, or the National Electric Code (NEC), is a US standard for the safe installation of electrical wiring and equipment. Chapter 5 of the code addresses electrical wiring in special occupancies and establishes various classifications. Of concern to the Midwest Generation facility are the classified areas defined by Class II (locations that are hazardous due to the presence of combustible dust), Division 1 (locations where hazardous concentrations are present in the air continuously, intermittently or periodically under normal operating conditions) and Group F (atmospheres containing carbon black, coal dust, or coke dust). These NEC provisions are related primarily to the use of proper enclosures, wiring trolleys, bronze hooks, stainless steel chain, or wire rope to provide the necessary spark resistance.

Electrical safety provisions of the plant were examined with respect to the above classification and it was determined that the coal stockpile did not require any special provisions. However, explosion-proof equipment has been installed in areas that contain enclosed rooms. This includes underground tunnels and the tripper room inside the plant. No area outside, including the stockpile and conveyors, is required to have explosion-proof equipment.

2.2.4 Conclusions

It is concluded that there is greater risk of sparking during the insertion fleeting operation than during series or parallel tow operations. It is also concluded that the operation of both barriers at the same time increases the potential for sparking during fleeting operations. There is consistently lower energy per pulse when parasitics 1, 2, 3 are all on. For coal-handling operations in the barge loading and fleeting area, and in the open storage area, the pertinent literature does not support concern for electrical sparking to create an explosion hazard.

2.3 Long tow voltage potential test (Objective 4)

2.3.1 Procedure

Long tow testing was completed for each of the barrier operational scenarios. In these tests a tow of five fully loaded barges in a single line made a minimum of three trips traversing from the fleeting area to above the aerial pipeline arch (Figure 13 and Figure 14).

This testing was designed to measure the voltage potential between the barges and tow boats within a long tow during the operation of all three barrier systems. This was accomplished by recording six channels of barge open circuit voltage potentials as the long tow traverses the barrier region. The voltage potentials between adjacent components of the long tow (V_{01}, V_{12}, V_{23}, V_{34}, V_{45}, and V_{56}) were measured as shown in Figure 14. Unlike previous testing, this time there were two towboats, one at each end of the five-barge tow. The boats are designated 0 and 6, the barges 1 – 5, which resulted in six measurement channels. All components of the tow were connected using wire rope, as is typical for transit on the canal.

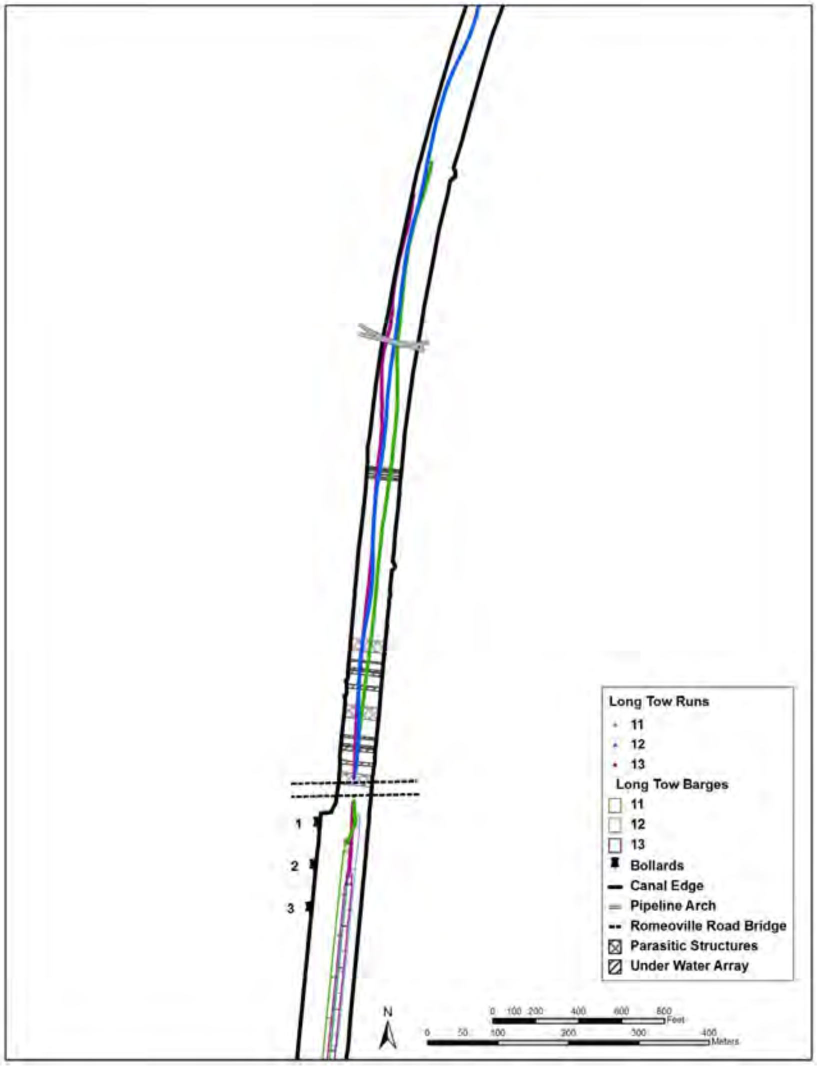

Figure 13. Long tow consisting of five barges and two towboats traversing the barriers on 8 and 10 February when the pulsers were in configuration Bravo and Parasitic 2 was on.

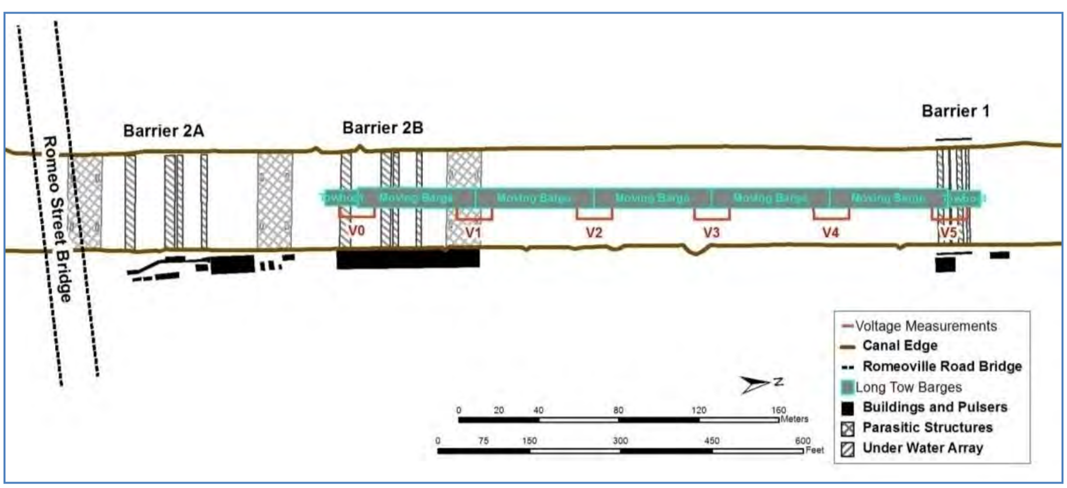

Figure 14. Diagram of five open-circuit voltage measurements (V_1–V_5) simultaneously captured for each barge in the long tow.

2.3.2 Analysis

The voltage plots were examined for each run, and the peak values when boats and barges passed over the barriers were noted.

2.3.3 Results and observations

Results of the long-tow voltage potential tests are listed in Chapter 4, Table 8, Table 9, and Table 10. The salient results are outlined below in Summary Table F.

Summary Table F. Outline of test results for long tow traversing Barriers IIA, IIB, and I, conducted on 8 and 10 February 2011 (see Tables 8–10, Chapter 4).

Pulser Configuration	Parasitic Settings			Range of voltage Differences between Barges		
	1	2	3	Over Barrier I	Over Barrier IIA	Over Barrier IIB
A	On	On	On	0.44V – 1.33V	1.60V – 3.23V	1.93V – 3.77V
A	On	Off	On	0.39V – 1.20V	1.26V – 3.45V	1.41V – 4.61V
B	On	On	On	0.55V – 1.15V	1.45V – 3.40V	1.37V – 5.99V
B	On	Off	On	0.36V – 1.70V	1.31V – 5.22V	1.86V – 4.56V
C	On	On	On	0.39V – 1.17V	1.09V – 2.93V	1.34V – 4.29V
C	On	Off	On	0.52V – 1.30V	1.22V – 4.36V	1.72V – 3.81V
D	On	On	Off	0.53V – 1.21V	1.47V – 4.64V	—

Long-tow voltage potential tests were not conducted for pulser configurations E and F. The primary data sampling and recording instrument failed, and the capabilities of the backup system were not sufficient (e.g., fewer recording channels) to adequately complete the long-tow tests. However, long-tow testing for pulser configurations E and F would be unlikely to show any new information. Previous testing indicated there is no significant risk associated with these tests, which are designed to identify the potential for sparking between barges traveling in a long-tow formation using wire rope to connect the barges.

The range of peak voltage differences measured over all three barriers in the B operational configuration does not appear to be significantly different than the range of peak voltage differences measured in the C configuration. The range of peak voltage differences when all three parasitics were connected was not significantly different than the range of voltage differences when only two parasitics were connected.

The highest voltage difference between barges, for all pulser configurations, was about 5 volts while passing over Barrier IIA, about 6 volts over Barrier IIB, and 1.7 volts over Barrier I. These low voltage values between barges indicate good electrical contact between the barge pairs. The peak voltage between towboat and barge is greater than between barges because the towboat-barge connection can have higher electrical resistance. The towboat has rubber impact bumpers that serve to electrically isolate it from the barge, so the sole electrical connection between the two is the wire rope. The barges are electrically connected not only by the wire rope but also through contact of their steel hulls.

2.3.4 Conclusions

The long tow voltage measurements suggest that there is a low probability for sparking between barges in a tow while traversing the barriers. These voltage differences are very small when compared to the soft line connection values of about 250 volts previously measured for Barrier I (see [1]). All barge-to-barge potentials are consistent with previous measurements and are below the limit of concern. The higher voltages measured between the barge and tugboats (Summary Table G) are the result of a higher resistive path between the tow and barge due to the rubber bumpers and cable-to-winch connections. Even though the measured voltages between tugboat and barge are higher than between barges, there is still a low probability of sparking because the barge is winched very tightly to the towboat. Observations of sparking have shown that it occurs when electrical contact is broken between towboat and barge, which would be unlikely.

Summary Table G. Voltage differences between outside barges and towboats.

Pulser Configuration	Range of voltage Differences between TOWBOAT and BARGE					
	Over Barrier I		Over Barrier IIA		Over Barrier IIB	
	1*	2**	1*	2**	1*	2**
A	0.79V – 0.9V	7.4V - 8.27V	2.22V – 2.67V	18.1V – 21.5V	2.91V – 3.31V	26.9V – 29.1V
B	0.77V – 10.1V	7.38V – 9.91V	2.52V – 29.7V	21.5V – 25.3V	2.8V – 35.1V	26.5V – 32.9V
C	9.72V – 11.5V	7.28V – 8.04V	26.4V – 30.3V	18.3V – 21.5V	33.1V – 36.6V	24.2V – 28V
D	10.3V – 11.6V	7.76V – 7.98V	30.7V – 33.1V	21.8V – 23.6V	——	——

*1: Potential between south towboat and Barge 1. ** 2: Potential between north towboat and Barge 5.

2.4 Shock potential at fleeting dock bollards (Objective 5)

2.4.1 Procedure

Voltage and current measurements at the Midwest Generation fleeting area were recorded for each of the six barrier operational scenarios. This test measured the voltages and currents between fixed barges in the fleeting area and the dock. Tests were conducted at the number 2 and 3 north tee-moorings.[5] A 500 Ω resistor was used for the current measurements.

2.4.2 Analysis

The voltage and current plots were examined for each record, and the peak values were noted.

2.4.3 Results and observations

Data for the shock potential tests are shown in Chapter 4, Table 11, and the results are presented in Summary Table H.

Summary Table H. Concise results for bollard voltage potential and 500-ohm current tests at fleeting area, conducted on 7 February 2011 (see Table 11, Chapter 4).

Pulser Configuration	Parasitic Settings			Peak voltage and Current at Bollards			
	1	2	3	Bollard 2		Bollard 3	
A (Feb 7)	On	On	On	6.3V	11.7 mA	3.0V	4.3 mA
A (Feb 7)	On	Off	On	7.9V	15.4 mA	3.8V	10.7 mA
B (Feb 7)	On	On	On	7.2V	11.3 mA	3.0V	4.3 mA
B (Feb 7)	On	Off	On	10.8V	17.0 mA	4.9V	7.4 mA
C (Feb 7)	On	On	On	6.9V	12.7 mA	4.3V	7.0 mA
C (Feb 7)	On	Off	On	11.2V	14.7 mA	7.9V	8.1 mA
D (Feb 7)	On	On	Off	3.0V	5.9 mA	1.6V	3.4 mA
E (June 15)	On	Off	On	3.3V	6.6mA	2.3V	5.6mA
F (June 15)	On	Off	On	3.5V	6.8mA	2.8V	5.2mA

[5] A tee-mooring is a large concrete-filled steel bollard with a steel crossbar that is used to tie barges and boats to the dock.

The 500 Ω resistance simulates the impedance of the human body from hand to foot. The hand to foot shock potential is referred to as the *touch potential*. Both peak voltage and current measurements were significantly lower at Bollard 3 than at Bollard 2, the latter being 200 ft (61 meters) closer to the barriers. There is no significant difference in either voltage potential or current between pulser configurations B and C. Having all three parasitics connected reduces the voltage and current for all pulser configurations at both bollard locations.

The maximum peak current was 17 mA and the maximum peak voltage was 11.2 volts. From Appendix B, Table B1 and Figure B1, these measurements are in the DC-2 range of IEC Publication 60479-1, where involuntary muscular contractions likely, especially when making, breaking or rapidly altering current flow, but usually without causing physiological harm.

2.4.4 Conclusions

There is no personnel shock hazard at the fleeting area due to barrier operation.

2.5 Corrosion potential (Objective 6)

2.5.1 Procedure

In order to evaluate the possibility of accelerated corrosion on in-water steel structures in the fleeting area due to barrier operation, corrosion potential measurements were made on a moored barge during the tow assembly scenarios shown in Figure 5. Hull voltage potentials were measured between a copper/copper sulfate reference electrode immersed in canal water at the stern corner on the starboard side of the moored barge and the steel hull, as diagrammed in Figure 6. The barge was fully loaded to achieve maximum hull exposure underwater.

These measurements were made at the time of the sparking potential tests. Because the barriers produce pulsing waveforms, an *IR-free measurement* was made. An IR-free measurement is one where the voltage drop (I is current, R is resistance) between the reference electrode and the structure (in this case, a barge hull) is eliminated. For a pulse, this is accomplished by taking the measurement at the instant the driving current goes to zero. This was done using an oscilloscope to view the potential waveform.

2.5.2 Analysis

Previous analysis of the hull-to-electrode corrosion potentials show a near-perfect "net zero" value, which confirms that the pulsed fish barrier electrical field, in effect, induces an alternating current signal during the cycle of the tow entering, passing over, and leaving the barrier. Thus, so long as the tow is electrically connected while entering, passing through, and continuing beyond the barrier by at least several hundred feet at a relatively uniform rate, no long-term corrosion effects should be of concern for tows moored at the fleeting area.

2.5.3 Results and observations

Results of the corrosion potential tests are listed in Chapter 4, Table 12.Anticipated corrosion activity for ferrous metal immersed in fresh water for several ranges of corrosion potentials are listed in Table 13, as derived from [9]. The measured corrosion potentials of 360 and 380 (-mV) indicate minimal corrosion activity.

2.5.4 Conclusions

Based on the previous analyses of the barge corrosion potentials passing over the barriers and the recent stationary barge corrosion potentials measured at the fleeting area (Bollard 2), there is no indication of a long-term corrosion problem for barges moored at the fleeting area.

2.6 Parasitic grid configuration testing (Objective 7)

2.6.1 Procedure

In an effort to determine the optimal configuration of the parasitic structures shown in Figure 11, the connections between these structures were varied throughout the other tests documented in this report. As previously described, the parasitic structures consist of three steel grids placed on concrete supports on the bottom of waterway.

From southernmost to northernmost locations, the grids are numbered 1, 2, and 3, respectively. Each grid is connected by metal cables welded to the grid structure and connecting it to an electrical bus on the western shore of the canal. There are several switches that allow each parasitic grid to be connected and disconnected from the bus. By closing each switch (on position), parasitics are connected to each other via the bus. By opening a switch (off position), a parasitic may be disconnected from the bus.

2.6.2 Results and observations

Analysis of pulse energy during the fleeting area sparking tests shows higher energy at the fleeting area when only two parasitics are connected versus when all three are connected. No significant change in energy was observed in simulated collision as the tow spanned both barriers. The largest hazard area was noted when all three parasitic structures were not connected.

2.6.3 Conclusions

These test results do not provide clear evidence to refute the barrier designer's recommendation that the optimal parasitic configuration is accomplished by connecting only two of the three parasitic structures: those directly adjacent to the active arrays.

3 Conclusions and Recommendations

Conclusions

Summarized below are the principal conclusions drawn for each of the seven barrier-testing objectives:

1. Operating Barriers IIA and IIB concurrently creates a larger area of risk to a person in the water than operating them individually.
2. No significant increase in sparking risk was found when barrier operating parameters are set to 2.3 V/in. at 30 Hz with 2.5 ms pulses versus 2.0 V/in. at 15 Hz with 6.5 ms pulses.
3. For coal-handling operations in the barge loading and fleeting area, and in the open storage area, the pertinent literature does not support concern that electrical sparking creates an explosion hazard.
4. When a tow that spans Barriers IIA and IIB collides with a barge in the fleeting area, there is a higher risk of sparking when both barriers are operating than when only Barrier IIA is operating.
5. No significant increase in risk of sparking was found for a long tow spanning Barriers IIA and IIB when both are operating as long as the tow does not collide with other metal objects.
6. No significant risk of personnel shock hazard in the fleeting area was found during barrier operations for any operating configuration.
7. Operation of the barriers does not adversely affect corrosion potential for in-water steel structures at the Midwest Generation fleeting area.
8. The optimal parasitic grid configuration (i.e., best field pattern, least energy consumption, and least danger of sparking and shock in the fleeting area), utilizes connections between only the two parasitic structures directly adjacent to the active arrays.

Recommendations

Regarding operation of the fish barrier, it is recommended that:

- When making rules for barge operations in the fleeting area, consideration be given to the finding that the pertinent literature does not support concern that electrical sparking creates an explosion hazard.

- When operating the pulsers, consideration be given to the finding that the optimal parasitic grid configuration utilizes connections between only the two parasitic structures directly adjacent to the active arrays.

It is further recommended that the U.S. Coast Guard consider the findings of this study when preparing Regulated Navigation Area (RNA) documents pertaining to navigation of the Chicago Sanitary and Ship Canal.

4 Unabridged Data Tables

Editor's note: the tables presented in this chapter represent the raw data from which the summary tables, used in the main text, were derived.

Table 1. Environmental conditions during testing.

Date	Time	Mean Temperature (°F)	Average Humidity (%)	Precipitation (in)	Water Temperature (°F)	Water Conductivity (µS/cm)	Water Resistivity (ohm-cm)
4 Feb 2011	0910	17	73	None	39	1732	577
4 Feb 2011	1105	26	82	None			
4 Feb 2011	1400	29	88	None			
4 Feb 2011	1600	26	89	None			
5 Feb 2011	0800	17	73	None	37	1307	765
5 Feb 2011	1030	25	82	None			
5 Feb 2011	1400	32	89	None	41	1560	641
5 Feb 2011	1600	30	90	None			
7 Feb 2011	0845	27	91	None	39	1575	635
7 Feb 2011	1100	39	98	None			
7 Feb 2011	1450	35	54	None	41	1715	583
7 Feb 2011	1630	31	54	None			
8 Feb 2011	0850	12	48	None	41	1733	577
8 Feb 2011	1100	20	27	None			
8 Feb 2011	1400	21	25	None			
8 Feb 2011	1600	14	26	None			
10 Feb 2011	0800	-2	27	None	41	1733	577
10 Feb 2011	1030	12	27	None			
10 Feb 2011	1400	19	25	None			
10 Feb 2011	1600	18	30	None			
11 Feb 2011	1000	22	36	None	43	1575	577
11 Feb 2011	1130	28	32	None			
11 Feb 2011	1400	26	35	None			
11 Feb 2011	1600	27	38	None			
12 Feb 2011	0900	33	52	None	43	2242	446
12 Feb 2011	1100	39	35	None			
12 Feb 2011	1400	39	37	None			
12 Feb 2011	1600	38	40	None			

Table 2. Pulser and parasitic configurations and approximate run times for field mapping, conducted on 11 and 12 February 2011, and 14 June 2011.

Run Time	Run	Location	Pulser Configuration	Parasitic 1	Parasitic 2	Parasitic 3
11 February 2011						
08:40 – 09:00	1	East Wall	B	Off	Off	Off
09:00 – 09:20	2	West Wall	B	Off	Off	Off
09:20 – 09:40	3	Center	B	Off	Off	Off
Aborted	4	West Wall	B	Off	Off	Off
09:45 – 10:00	5	West Wall	B	Off	Off	Off
10:00 – 10:25	6	East Wall	B	Off	Off	Off
10:25 – 10:40	7	Center	B	Off	Off	Off
10:40 – 11:00	8	Center	B	On	Off	On
13:15 – 13:35	9	East Wall	B	On	Off	On
13:35 – 13:50	10	West Wall	B	On	Off	On
13:50 – 14:05	11	Center	B	On	Off	On
14:05 – 14:20	12	West Wall	B	On	Off	On
14:20 – 14:35	13	East Wall	B	On	Off	On
14:35 – 14:50	14	West Wall	B	On	On	On
14:50 – 15:05	15	East Wall	B	On	On	On
15:05 – 15:20	16	Center	B	On	On	On
15:20 – 15:35	17	East Wall	B	On	On	On
15:35 – 15:45	18	West Wall	B	On	On	On
15:45 – 16:00	19	Center	B	On	On	On
12 February 2011						
09:10 – 09:30	1	East Wall	D	On	On	Off
09:30 – 09:45	2	West Wall	D	On	On	Off
09:45 – 10:00	3	Center	D	On	On	Off
10:00 – 10:10	4	West Wall	D	On	On	Off
10:10 – 10:25	5	East Wall	D	On	On	Off
10:25 – 10:35	6	Center	D	On	On	Off
10:35 – 10:45	7	East Wall	A	On	Off	On
10:45 – 11:00	8	West Wall	A	On	Off	On

Run Time	Run	Location	Pulser Configuration	Parasitic 1	Parasitic 2	Parasitic 3
13:25 – 13:45	9	Center	A	On	Off	On
13:45 – 13:55	10	West Wall	A	On	Off	On
13:55 – 14:10	11	East Wall	A	On	Off	On
14:10 – 14:20	12	Center	A	On	Off	On
14:20 – 14:40	13	East Wall	C	On	Off	On
14:40 – 14:55	14	West Wall	C	On	Off	On
14:55 – 15:15	15	Center	C	On	Off	On
15:15 – 15:30	16	West Wall	C	On	Off	On
15:30 – 15:50	17	East Wall	C	On	Off	On
15:50 – 16:00	18	Center	C	On	Off	On
16:00 – 16:15	19	Center	C	On	On	On
14 June 2011						
08:59 - 09:19	8	East Wall	E	On	Off	On
09:20 -0 9:31	9	West Wall	E	On	Off	On
09:31 - 09:46	10	Center	E	On	Off	On
09:46 - 09:56	11	West Wall	E	On	Off	On
09:58 - 10:07	12	East Wall	E	On	Off	On
10:08 - 10:23	13	Center	E	On	Off	On
13:03 - 13:23	14	East Wall	F	On	Off	On
13:23 - 13:35	15	West Wall	F	On	Off	On
13:35 - 13:51	16	Center	F	On	Off	On
13:51 - 14:05	17	West Wall	F	On	Off	On
14:06 - 14:19	18	East Wall	F	On	Off	On
14:19 - 14:36	19	Center	F	On	Off	On
16:08 - 16:25	26	East Wall	F	On	Off	On
16:26 - 16:34	27	West Wall	F	On	Off	On
16:35 - 16:45	28	Center	F	On	Off	On
16:45 - 16:51	29	West Wall	F	On	Off	On
16:52 - 17:02	30	East Wall	F	On	Off	On
17:02 - 17:15	31	Center	F	On	Off	On

Table 3. Locations of Barriers IIA and IB voltage gradients sufficient to cause harmful physiological effects.

Run Date	Pulser (Parasitic) Configuration	Location	Voltage Gradient	Range in ft (m)	Downstream Distance with respect to IIB in ft (m)*	Upstream Distance with respect to IIB in ft (m)*
1 (Feb 11th)	B (Off, Off, Off)	East Wall	≥0.05 V/in	1,361 (415)	-820 (-250)	541 (165)
2 (Feb 11th)	B (Off, Off, Off)	West Wall	≥0.05 V/in	1,361 (415)	-820 (-250)	541 (165)
3 (Feb 11th)	B (Off, Off, Off)	Center	≥0.05 V/in	1,345 (410)	-820 (-250)	525 (160)
4 (Feb 11th)**	B (Off, Off, Off)	West Wall	≥0.05 V/in	-	-	-
5 (Feb 11th)	B (Off, Off, Off)	West Wall	≥0.05 V/in	1,394 (425)	-853 (-260)	541 (165)
6 (Feb 11th)	B (Off, Off, Off)	East Wall	≥0.05 V/in	1,362 (415)	-837 (-255)	525 (160)
7 (Feb 11th)	B (Off, Off, Off)	Center	≥0.05 V/in	1,378 (420)	-837 (-255)	541 (165)
	B (Off, Off, Off)	**Greatest Extent**	≥0.05 V/in	**1,394 (425)**	**-853 (-260)**	**541 (165)**
8 (Feb 11th)	B (On, Off, On)	Center	≥0.05 V/in	1,181 (360)	-820 (-250)	361 (110)
9 (Feb 11th)	B (On, Off, On)	East Wall	≥0.05 V/in	1,116 (340)	-804 (-245)	312 (95)
10 (Feb 11th)	B (On, Off, On)	West Wall	≥0.05 V/in	1,115 (340)	-771 (-235)	344 (105)
11 (Feb 11th)	B (On, Off, On)	Center	≥0.05 V/in	1,115 (340)	-771 (-235)	344 (105)
12 (Feb 11th)	B (On, Off, On)	West Wall	≥0.05 V/in	1,164 (355)	-787 (-240)	377 (115)
13 (Feb 11th)	B (On, Off, On)	East Wall	≥0.05 V/in	1,116 (340)	-804 (-245)	312 (95)
	B (On, Off, On)	**Greatest Extent**	≥0.05 V/in	**1,197 (365)**	**-820 (-250)**	**377 (115)**
14 (Feb 11th)	B (On, On, On)	West Wall	≥0.05 V/in	1,099 (335)	-755 (-230)	344 (105)
15 (Feb 11th)	B (On, On, On)	East Wall	≥0.05 V/in	1,083 (330)	-771 (-235)	312 (95)
16 (Feb 11th)	B (On, On, On)	Center	≥0.05 V/in	1.099 (335)	-755 (-230)	344 (105)
17 (Feb 11th)	B (On, On, On)	East Wall	≥0.05 V/in	1.066 (325)	-787 (-240)	279 (85)
18 (Feb 11th)**	B (On, On, On)	West Wall	≥0.05 V/in	-	-	-
19 (Feb 11th)	B (On, On, On)	Center	≥0.05 V/in	1,083 (330)	-755 (-230)	328 (100)
	B (On, On, On)	**Greatest extent**	≥0.05 V/in	**1,131 (345)**	**-787 (-240)**	**344 (105)**
1 (Feb 12th)	D (On, On, Off)	East Wall	≥0.05 V/in	493 (150)	-591 (-180)	-98 (-30)
2 (Feb 12th)	D (On, On, Off)	West Wall	≥0.05 V/in	558 (170)	-640 (-195)	-82 (-25)
3 (Feb 12th)	D (On, On, Off)	Center	≥0.05 V/in	444 (135)	-542 (-165)	-98 (-30)
4 (Feb 12th)	D (On, On, Off)	West Wall	≥0.05 V/in	444 (135)	-542 (-165)	-98 (-30)
5 (Feb 12th)	D (On, On, Off)	East Wall	≥0.05 V/in	591 (180)	-689 (-210)	-98 (-30)
6 (Feb 12th)	D (On, On, Off)	Center	≥0.05 V/in	525 (160)	-607 (-185)	-98 (-30)

Run Date	Pulser (Parasitic) Configuration	Location	Voltage Gradient	Range in ft (m)	Downstream Distance with respect to IIB in ft (m)*	Upstream Distance with respect to IIB in ft (m)*
	D (On, On, Off)	**Greatest extent**	≥0.05 V/in	**607 (185)**	**-689 (-210)**	**-82 (-25)**
7 (Feb 12th)	A (On, Off, On)	East Wall	≥0.05 V/in	1,148 (350)	-804 (-245)	344 (105)
8 (Feb 12th)	A (On, Off, On)	West wall	≥0.05 V/in	1,182 (360)	-788 (-240)	394 (120)
9 (Feb 12th)	A (On, Off, On)	Center	≥0.05 V/in	1,198 (365)	-804 (-245)	394 (120)
10 (Feb 12th)	A (On, Off, On)	West Wall	≥0.05 V/in	1,198 (365)	-788 (-240)	410 (125)
11 (Feb 12th)	A (On, Off, On)	East Wall	≥0.05 V/in	1,133 (345)	-821 (-250)	312 (95)
12 (Feb 12th)	A (On, Off, On)	Center	≥0.05 V/in	1,198 (365)	-804 (-245)	394 (120)
	A (On, Off, On)	**Greatest extent**	≥0.05 V/in	**1,231 (375)**	**-821 (-250)**	**410 (125)**
13 (Feb 12th)	C (On, Off, On)	East Wall	≥0.05 V/in	1,083 (330)	-804 (-245)	279 (85)
14 (Feb 12th)	C (On, Off, On)	West Wall	≥0.05 V/in	1,132 (345)	-771 (-235)	361 (110)
15 (Feb 12th)	C (On, Off, On)	Center	≥0.05 V/in	1,148 (350)	-804 (-245)	344 (105)
16 (Feb 12th)	C (On, Off, On)	West Wall	≥0.05 V/in	1,149 (350)	-788 (-240)	361 (110)
17 (Feb 12th)	C (On, Off, On)	East Wall	≥0.05 V/in		-	-
18 (Feb 12th)	C (On, Off, On)	Center	≥0.05 V/in		-	-
	C (On, Off, On)	**Greatest extent**	≥0.05 V/in	**1,165 (355)**	**-804 (-245)**	**361 (110)**
19 (Feb 12th)	C (On, On, On)	Center	≥0.05 V/in	1,034 (315)	-706 (-215)	328 (100)
		Greatest extent	≥0.05 V/in	**1,034 (315)**	**-706 (-215)**	**328 (100)**
8 (June 14th)	E (On, Off, On)	East Wall	≥0.05 V/in	988 (301)	-712 (-217)	276 (84)
9 (June 14th)	E (On, Off, On)	West Wall	≥0.05 V/in	1033 (315)	-738 (-225)	295 (90)
10 (June 14th)	E (On, Off, On)	Center	≥0.05 V/in	1050 (320)	-755 (-230)	295 (90)
11 (June 14th)	E (On, Off, On)	West Wall	≥0.05 V/in	1017 (310)	-722 (-220)	295 (90)
12 (June 14th)	E (On, Off, On)	East Wall	≥0.05 V/in	1007 (307)	-738 (-225)	269 (82)
13 (June 14th)	E (On, Off, On)	Center	≥0.05 V/in	1033 (315)	-738 (-225)	295 (90)
	E (On, Off, On)	**Greatest Extent**	≥0.05 V/in	**1050 (320)**	**-755 (-230)**	**295 (90)**
14 (June 14th)	F (On, Off, On)	East Wall	≥0.05 V/in	984 (300)	-722 (-220)	262 (80)
15 (June 14th)	F (On, Off, On)	West Wall	≥0.05 V/in	1001 (305)	-722 (-220)	279 (85)
17 (June 14th)	F (On, Off, On)	West Wall	≥0.05 V/in	968 (295)	-722 (-220)	246 (75)
18 (June 14th)	F (On, Off, On)	East Wall	≥0.05 V/in	968 (295)	-705 (-215)	262 (80)
19 (June 14th)	F (On, Off, On)	Center	≥0.05 V/in	968 (295)	-689 (-210)	279 (85)

Run Date	Pulser (Parasitic) Configuration	Location	Voltage Gradient	Range in ft (m)	Downstream Distance with respect to IIB in ft (m)*	Upstream Distance with respect to IIB in ft (m)*
26 (June 14th)	F (On, Off, On)	East Wall	≥0.05 V/in	968 (295)	-705 (-215)	262 (80)
27 (June 14th)	F (On, Off, On)	West Wall	≥0.05 V/in	984 (300)	-705 (-215)	279 (85)
28 (June 14th)	F (On, Off, On)	Center	≥0.05 V/in	984 (300)	-738 (-225)	246 (75)
29 (June 14th)	F (On, Off, On)	West Wall	≥0.05 V/in	984 (300)	-705 (-215)	279 (85)
30 (June 14th)	F (On, Off, On)	East Wall	≥0.05 V/in	984 (300)	-722 (-220)	262 (80)
31 (June 14th)	F (On, Off, On)	Center	≥0.05 V/in	984 (300)	-705 (-215)	279 (85)
	F (On, Off, On)	**Greatest Extent**	≥0.05 V/in	**1001 (305)**	**-722 (-220)**	**279 (85)**
1 (Feb 11th)	B (Off, Off, Off)	East Wall	≥0.03 V/in	2,052 (625)***	-903 (-275)***	1,149 (350)***
2 (Feb 11th)	B (Off, Off, Off)	West Wall	≥0.03 V/in	2,052 (625)***	-903 (-275)***	1,149 (350)***
3 (Feb 11th)	B (Off, Off, Off)	Center	≥0.03 V/in	2,084 (635)***	-919 (-280)***	1,165 (355)***
4 (Feb 11th)**	B (Off, Off, Off)	West Wall	≥0.03 V/in	-	-	-
5 (Feb 11th)	B (Off, Off, Off)	West Wall	≥0.03 V/in	2,068 (630)***	-919 (-280)***	1,149 (350)***
6 (Feb 11th)	B (Off, Off, Off)	East Wall	≥0.03 V/in	2,019 (615)***	-919 (-280)***	1,100 (335)***
7 (Feb 11th)	B (Off, Off, Off)	Center	≥0.03 V/in	2,068 (630)***	-919 (-280)***	1,149 (350)***
	B (Off, Off, Off)	**Greatest Extent**	≥0.03 V/in	**2,084 (635)*** **	**-919 (-280)*** **	**1,165 (355)*** **
8 (Feb 11th)	B (On, Off, On)	Center	≥0.03 V/in	1,412 (430)	-903 (-275)	509 (155)
9 (Feb 11th)	B (On, Off, On)	East Wall	≥0.03 V/in	1,445 (440)	-903 (-275)	542 (165)
10 (Feb 11th)	B (On, Off, On)	West Wall	≥0.03 V/in	1,461 (445)	-919 (-280)	542 (165)
11 (Feb 11th)	B (On, Off, On)	Center	≥0.03 V/in	2,018 (615)***	-886 (-270)***	1,132 (345)***
12 (Feb 11th)	B (On, Off, On)	West Wall	≥0.03 V/in	1,428 (435)	-886 (-270)	542 (165)
13 (Feb 11th)	B (On, Off, On)	East Wall	≥0.03 V/in	1,412 (430)	-903 (-275)	509 (155)
	B (On, Off, On)	**Greatest Extent**	≥0.03 V/in	**2,051 (625)*** **	**-919 (-280)*** **	**1,132 (345)*** **
14 (Feb 11th)	B (On, On, On)	West Wall	≥0.03 V/in	1,346 (410)	-837 (-255)	509 (155)
15 (Feb 11th)	B (On, On, On)	East Wall	≥0.03 V/in	1,363 (415)	-903 (-275)	460 (140)
16 (Feb 11th)	B (On, On, On)	Center	≥0.03 V/in	1,379 (420)	-870 (-265)	509 (155)
17 (Feb 11th)	B (On, On, On)	East Wall	≥0.03 V/in	1,297 (395)	-854 (-260)	443 (135)
18 (Feb11th)**	B (On, On, On)	West Wall	≥0.03 V/in	-	-	-
19 (Feb 11th)	B (On, On, On)	Center	≥0.03 V/in	1,347 (410)	-854 (-260)	493 (150)
	B (On, On, On)	**Greatest extent**	≥0.03 V/in	**1,412 (430)**	**-903 (-275)**	**509 (155)**

Run Date	Pulser (Parasitic) Configuration	Location	Voltage Gradient	Range in ft (m)	Downstream Distance with respect to IIB in ft (m)*	Upstream Distance with respect to IIB in ft (m)*
1 (Feb 12th)	D (On, On, Off)	East Wall	≥0.03 V/in	657 (200)	-722 (-220)	-65 (-20)
2 (Feb 12th)	D (On, On, Off)	West Wall	≥0.03 V/in	657 (200)	-722 (-220)	-65 (-20)
3 (Feb 12th)	D (On, On, Off)	Center	≥0.03 V/in	623 (190)	-706 (-215)	-83 (-25)
4 (Feb 12th)	D (On, On, Off)	West Wall	≥0.03 V/in	657 (200)	-740 (-225)	-83 (-25)
5 (Feb 12th)	D (On, On, Off)	East Wall	≥0.03 V/in	639 (195)	-722 (-220)	-83 (-25)
6 (Feb 12th)	D (On, On, Off)	Center	≥0.03 V/in	639 (195)	-722 (-220)	-83 (-25)
	D (On, On, Off)	**Greatest extent**	≥0.03 V/in	**657 (200)**	**-722 (-220)**	**-65 (-20)**
7 (Feb 12th)	A (On, Off, On)	East Wall	≥0.03 V/in	1,161 (445)	-903 (-275)	558 (170)
8 (Feb 12th)	A (On, Off, On)	West wall	≥0.03 V/in	1,444 (340)	-886 (-270)	558 (170)
9 (Feb 12th)	A (On, Off, On)	Center	≥0.03 V/in	2,035 (620)	-903 (-275)***	1,132 (345)***
10 (Feb 12th)	A (On, Off, On)	West Wall	≥0.03 V/in	1,444 (340)	-886 (-270)	558 (170)
11 (Feb 12th)	A (On, Off, On)	East Wall	≥0.03 V/in	1,478 (450)	-936 (-285)	542 (165)
12 (Feb 12th)	A (On, Off, On)	Center	≥0.03 V/in	2,052 (625)	-919 (-280)***	1,132 (345)***
	A (On, Off, On)	**Greatest extent**	≥0.03 V/in	**2,068 (630)**	**-936 (-285)**	**1,132 (345)*** **
13 (Feb 12th)	C (On, Off, On)	East Wall	≥0.03 V/in	N/A	N/A	N/A
14 (Feb 12th)	C (On, Off, On)	West Wall	≥0.03 V/in	N/A	N/A	N/A
15 (Feb 12th)	C (On, Off, On)	Center	≥0.03 V/in	N/A	N/A	N/A
16 (Feb 12th)	C (On, Off, On)	West Wall	≥0.03 V/in	N/A	N/A	N/A
17 (Feb 12th)	C (On, Off, On)	East Wall	≥0.03 V/in	N/A	N/A	N/A
18 (Feb 12th)	C (On, Off, On)	Center	≥0.03 V/in	N/A	N/A	N/A
	C (On, Off, On)	**Greatest extent**	≥0.03 V/in	**N/A**	**N/A**	**N/A**
19 (Feb 12th)	C (On, On, On)	Center	≥0.03 V/in	N/A	N/A	N/A
		Greatest extent	≥0.03 V/in	**N/A**	**N/A**	**N/A**
8 (June14th)	E (On, Off, On)	East Wall	≥0.03 V/in	1050 (320)	-771 (-235)	279 (85)
9 (June 14th)	E (On, Off, On)	West Wall	≥0.03 V/in	1148 (350)	-787 (-240)	361 (110)
10 (June 14th)	E (On, Off, On)	Center	≥0.03 V/in	1181 (360)	-820 (-250)	361 (110)
11 (June 14th)	E (On, Off, On)	West Wall	≥0.03 V/in	1165 (355)	-787 (-240)	377 (115)
12 (June 14th)	E (On, Off, On)	East Wall	≥0.03 V/in	1083 (330)	-804 (-245)	279 (85)
13 (June 14th)	E (On, Off, On)	Center	≥0.03 V/in	1165 (355)	-820 (-250)	344 (105)

Run Date	Pulser (Parasitic) Configuration	Location	Voltage Gradient	Range in ft (m)	Downstream Distance with respect to IIB in ft (m)*	Upstream Distance with respect to IIB in ft (m)*
	E (On, Off, On)	**Greatest Extent**	≥0.03 V/in	**1181 (360)**	**-820 (-250)**	**361 (110)**
14 (June 14th)	F (On, Off, On)	East Wall	≥0.03 V/in	1089 (332)	-820 (-250)	269 (82)
15 (June 14th)	F (On, Off, On)	West Wall	≥0.03 V/in	1132 (345)	-771 (-235)	361 (110)
17 (June 14th)	F (On, Off, On)	West Wall	≥0.03 V/in	1083 (330)	-771 (-235)	312 (95)
18 (June 14th)	F (On, Off, On)	East Wall	≥0.03 V/in	1066 (325)	-787 (-240)	279 (85)
19 (June 14th)	F (On, Off, On)	Center	≥0.03 V/in	1115 (340)	-787 (-240)	328 (100)
26 (June 14th)	F (On, Off, On)	East Wall	≥0.03 V/in	1050 (320)	-771 (-235)	279 (85)
27 (June 14th)	F (On, Off, On)	West Wall	≥0.03 V/in	1115 (340)	-755 (-230)	361 (110)
28 (June 14th)	F (On, Off, On)	Center	≥0.03 V/in	1083 (340)	-820 (-250)	262 (80)
29 (June 14th)	F (On, Off, On)	West Wall	≥0.03 V/in	1132 (345)	-771 (-235)	361 (110)
30 (June 14th)	F (On, Off, On)	East Wall	≥0.03 V/in	1066 (325)	-787 (-240)	279 (85)
31 (June 14th)	F (On, Off, On)	Center	≥0.03 V/in	1115 (340)	-787 (-240)	328 (100)
	F (On, Off, On)	**Greatest Extent**	≥0.03 V/in	**1132 (345)**	**-771 (-235)**	**361 (110)**
1 (Feb 11th)	B (Off, Off, Off)	East Wall	≥0.02 V/in	N/A	N/A	N/A
2 (Feb 11th)	B (Off, Off, Off)	West Wall	≥0.02 V/in	N/A	N/A	N/A
3 (Feb 11th)	B (Off, Off, Off)	Center	≥0.02 V/in	N/A	N/A	N/A
4 (Feb 11th)**	B (Off, Off, Off)	West Wall	≥0.02 V/in	N/A	N/A	N/A
5 (Feb 11th)	B (Off, Off, Off)	West Wall	≥0.02 V/in	N/A	N/A	N/A
6 (Feb 11th)	B (Off, Off, Off)	East Wall	≥0.02 V/in	N/A	N/A	N/A
7 (Feb 11th)	B (Off, Off, Off)	Center	≥0.02 V/in	N/A	N/A	N/A
	B (Off, Off, Off)	**Greatest Extent**	≥0.02 V/in	**N/A**	**N/A**	**N/A**
8 (Feb 11th)	B (On, Off, On)	Center	≥0.02 V/in	N/A	N/A	N/A
9 (Feb 11th)	B (On, Off, On)	East Wall	≥0.02 V/in	N/A	N/A	N/A
10 (Feb 11th)	B (On, Off, On)	West Wall	≥0.02 V/in	N/A	N/A	N/A
11 (Feb 11th)	B (On, Off, On)	Center	≥0.02 V/in	N/A	N/A	N/A
12 (Feb 11th)	B (On, Off, On)	West Wall	≥0.02 V/in	N/A	N/A	N/A
13 (Feb 11th)	B (On, Off, On)	East Wall	≥0.02 V/in	N/A	N/A	N/A
	B (On, Off, On)	**Greatest Extent**	≥0.02 V/in	**N/A**	**N/A**	**N/A**
14 (Feb 11th)	B (On, On, On)	West Wall	≥0.02 V/in	N/A	N/A	N/A

Run Date	Pulser (Parasitic) Configuration	Location	Voltage Gradient	Range in ft (m)	Downstream Distance with respect to IIB in ft (m)*	Upstream Distance with respect to IIB in ft (m)*
15 (Feb 11th)	B (On, On, On)	East Wall	≥0.02 V/in	N/A	N/A	N/A
16 (Feb 11th)	B (On, On, On)	Center	≥0.02 V/in	N/A	N/A	N/A
17 (Feb 11th)	B (On, On, On)	East Wall	≥0.02 V/in	N/A	N/A	N/A
18 (Feb 11th)**	B (On, On, On)	West Wall	≥0.02 V/in	N/A	N/A	N/A
19 (Feb 11th)	B (On, On, On)	Center	≥0.02 V/in	N/A	N/A	N/A
	B (On, On, On)	**Greatest extent**	≥0.02 V/in	**N/A**	**N/A**	**N/A**
1 (Feb 12th)	D (On, On, Off)	East Wall	≥0.02 V/in	N/A	N/A	N/A
2 (Feb 12th)	D (On, On, Off)	West Wall	≥0.02 V/in	N/A	N/A	N/A
3 (Feb 12th)	D (On, On, Off)	Center	≥0.02 V/in	N/A	N/A	N/A
4 (Feb 12th)	D (On, On, Off)	West Wall	≥0.02 V/in	N/A	N/A	N/A
5 (Feb 12th)	D (On, On, Off)	East Wall	≥0.02 V/in	N/A	N/A	N/A
6 (Feb 12th)	D (On, On, Off)	Center	≥0.02 V/in	N/A	N/A	N/A
	D (On, On, Off)	**Greatest extent**	≥0.02 V/in	**N/A**	**N/A**	**N/A**
7 (Feb 12th)	A (On, Off, On)	East Wall	≥0.02 V/in	1658 (505)	-985 (-300)	673 (205)
8 (Feb 12th)	A (On, Off, On)	West wall	≥0.02 V/in	1658 (505)	-952 (-290)	706 (215)
9 (Feb 12th)	A (On, Off, On)	Center	≥0.02 V/in	1674 (510)	-968 (-295)	706 (215)
10 (Feb 12th)	A (On, Off, On)	West Wall	≥0.02 V/in	1674 (510)	-968 (-295)	706 (215)
11 (Feb 12th)	A (On, Off, On)	East Wall	≥0.02 V/in	1674 (510)	-1001 (-305)	673 (205)
12 (Feb 12th)	A (On, Off, On)	Center	≥0.02 V/in	1707 (520)	-1001 (-305)	706 (215)
	A (On, Off, On)	**Greatest extent**	≥0.02 V/in	**1707 (520)**	**-1001 (-305)**	**706 (215)**
13 (Feb 12th)	C (On, Off, On)	East Wall	≥0.02 V/in	1641 (500)	-968 (-295)	673 (205)
14 (Feb 12th)	C (On, Off, On)	West Wall	≥0.02 V/in	1592 (485)	-968 (-295)	624 (190)
15 (Feb 12th)	C (On, Off, On)	Center	≥0.02 V/in	1576 (480)	-985 (-300)	608 (185)
16 (Feb 12th)	C (On, Off, On)	West Wall	≥0.02 V/in	1625 (495)	-968 (-295)	657 (200)
17 (Feb 12th)	C (On, Off, On)	East Wall	≥0.02 V/in	**	**	**
18 (Feb 12th)	C (On, Off, On)	Center	≥0.02 V/in	**	**	**
	C (On, Off, On)	**Greatest extent**	≥0.02 V/in	**1658 (505)**	**-985 (-300)**	**673 (205)**
19 (Feb 12th)	C (On, On, On)	Center	≥0.02 V/in	1477 (450)	-837 (-255)	640 (195)
		Greatest extent	≥0.02 V/in	**1477 (450)**	**-837 (-255)**	**640 (195)**

Run Date	Pulser (Parasitic) Configuration	Location	Voltage Gradient	Range in ft (m)	Downstream Distance with respect to IIB in ft (m)*	Upstream Distance with respect to IIB in ft (m)*
8 (June 14th)	E (On, Off, On)	East Wall	≥0.02 V/in	N/A	N/A	N/A
9 (June 14th)	E (On, Off, On)	West Wall	≥0.02 V/in	N/A	N/A	N/A
10 (June 14th)	E (On, Off, On)	Center	≥0.02 V/in	N/A	N/A	N/A
11 (June 14th)	E (On, Off, On)	West Wall	≥0.02 V/in	N/A	N/A	N/A
12 (June 14th)	E (On, Off, On)	East Wall	≥0.02 V/in	N/A	N/A	N/A
13 (June 14th)	E (On, Off, On)	Center	≥0.02 V/in	N/A	N/A	N/A
	E (On, Off, On)	**Greatest Extent**	≥0.02 V/in	**N/A**	**N/A**	**N/A**
14 (June 14th)	F (On, Off, On)	East Wall	≥0.02 V/in	1194 (364)	-919 (-280)	276 (84)
15 (June 14th)	F (On, Off, On)	West Wall	≥0.02 V/in	1247 (380)	-820 (-250)	427 (130)
17 (June 14th)	F (On, Off, On)	West Wall	≥0.02 V/in	1148 (350)	-787 (-240)	361 (110)
18 (June 14th)	F (On, Off, On)	East Wall	≥0.02 V/in	1181 (360)	-886 (-270)	295 (90)
19 (June 14th)	F (On, Off, On)	Center	≥0.02 V/in	1247 (380)	-853 (-260)	394 (120)
26 (June 14th)	F (On, Off, On)	East Wall	≥0.02 V/in	1165 (355)	-886 (-270)	279 (85)
27 (June 14th)	F (On, Off, On)	West Wall	≥0.02 V/in	1214 (370)	-837 (-240)	427 (130)
28 (June 14th)	F (On, Off, On)	Center	≥0.02 V/in	1214 (370)	-886 (-270)	328 (100)
29 (June 14th)	F (On, Off, On)	West Wall	≥0.02 V/in	1263 (385)	-837 (-255)	427 (130)
30 (June 14th)	F (On, Off, On)	East Wall	≥0.02 V/in	1165 (355)	-886 (-270)	279 (85)
31 (June 14th)	F (On, Off, On)	Center	≥0.02 V/in	1296 (395)	-886 (-270)	410 (125)
	F (On, Off, On)	**Greatest Extent**	≥0.02 V/in	**1296 (395)**	**-886 (-270)**	**410 (125)**

* Distances are from a zero point at the center of Barrier IIB's narrow array. This point is shown on Figure 3.

** Electric field measurements not included due to lack of GPS measurements.

*** Range of harmful effects extends from south of Barrier IIA to north of Barrier I, there is no safe zone between barriers.

Table 4. Locations of Barrier I voltage gradients sufficient to cause harmful physiological effects.

Run (Date)	Pulser (Parasitic) Configuration	Location	Voltage Gradient	Range in ft (m)	Downstream Distance with respect to IIB in ft (m)*	Upstream Distance with respect to IIB in ft (m)*
1 (Feb 11th)	B (Off, Off, Off)	East Wall	≥0.05 V/in	280 (85)	754 (230)	1,034 (315)
2 (Feb 11th)	B (Off, Off, Off)	West Wall	≥0.05 V/in	280 (85)	754 (230)	1,034 (315)
3 (Feb 11th)	B (Off, Off, Off)	Center	≥0.05 V/in	264 (80)	770 (235)	1,034 (315)
4 (Feb 11th)	B (Off, Off, Off)	West Wall	≥0.05 V/in	-	-	-
5 (Feb 11th)	B (Off, Off, Off)	West Wall	≥0.05 V/in	247 (75)	770 (235)	1,017 (310)
6 (Feb 11th)	B (Off, Off, Off)	East Wall	≥0.05 V/in	215 (65)	770 (235)	985 (300)
7 (Feb 11th)	B (Off, Off, Off)	Center	≥0.05 V/in	296 (90)	738 (225)	1,034 (315)
	B (Off, Off, Off)	**Greatest Extent**	≥0.05 V/in	**296 (90)**	**738 (225)**	**1034 (315)**
8 (Feb 11th)	B (On, Off, On)	Center	≥0.05 V/in	296 (90)	738 (225)	1,034 (315)
9 (Feb 11th)	B (On, Off, On)	East Wall	≥0.05 V/in	263 (80)	754 (230)	1,017 (310)
10 (Feb 11th)	B (On, Off, On)	West Wall	≥0.05 V/in	246 (75)	771 (235)	1,017 (310)
11 (Feb 11th)	B (On, Off, On)	Center	≥0.05 V/in	230 (70)	787 (240)	1,017 (310)
12 (Feb 11th)	B (On, Off, On)	West Wall	≥0.05 V/in	247 (75)	787 (240)	1,034 (315)
13 (Feb 11th)	B (On, Off, On)	East Wall	≥0.05 V/in	230 (70)	771 (235)	1,001 (305)
	B (On, Off, On)	**Greatest Extent**	≥0.05 V/in	**296 (90)**	**738 (225)**	**1,034 (315)**
14 (Feb 11th)	B (On, On, On)	West Wall	≥0.05 V/in	230 (70)	787 (240)	1,017 (310)
15 (Feb 11th)	B (On, On, On)	East Wall	≥0.05 V/in	246 (75)	771 (235)	1,017 (310)
16 (Feb 11th)	B (On, On, On)	Center	≥0.05 V/in	263 (80)	771 (235)	1,034 (315)
17 (Feb 11th)	B (On, On, On)	East Wall	≥0.05 V/in	246 (75)	771 (235)	1,017 (310)
18 (Feb 11th)**	B (On, On, On)	West Wall	≥0.05 V/in	-	-	-
19 (Feb 11th)	B (On, On, On)	Center	≥0.05 V/in	247 (75)	787 (240)	1,034 (315)
	B (On, On, On)	**Greatest extent**	≥0.05 V/in	**263 (80)**	**771 (235)**	**1,034 (315)**
1 (Feb 12th)	D (On, On, Off)	East Wall	≥0.05 V/in	230 (70)	787 (240)	1,017 (310)
2 (Feb 12th)	D (On, On, Off)	West Wall	≥0.05 V/in	214 (65)	803 (245)	1,017 (310)
3 (Feb 12th)	D (On, On, Off)	Center	≥0.05 V/in	247 (75)	787 (240)	1,034 (315)
4 (Feb 12th)	D (On, On, Off)	West Wall	≥0.05 V/in	214 (65)	803 (245)	1,017 (310)
5 (Feb 12th)	D (On, On, Off)	East Wall	≥0.05 V/in	230 (70)	787 (240)	1,017 (310)
6 (Feb 12th)	D (On, On, Off)	Center	≥0.05 V/in	214 (65)	803 (245)	1,017(310)

Run (Date)	Pulser (Parasitic) Configuration	Location	Voltage Gradient	Range in ft (m)	Downstream Distance with respect to IIB in ft (m)*	Upstream Distance with respect to IIB in ft (m)*
	D (On, On, Off)	**Greatest extent**	≥0.05 V/in	**247 (75)**	**787 (240)**	**1,034 (315)**
7 (Feb 12th)	A (On, Off, On)	East Wall	≥0.05 V/in	263 (80)	754 (230)	1,017 (310)
8 (Feb 12th)	A (On, Off, On)	West wall	≥0.05 V/in	214 (65)	803 (245)	1,017 (310)
9 (Feb 12th)	A (On, Off, On)	Center	≥0.05 V/in	214 (65)	803 (245)	1,017 (310)
10 (Feb 12th)	A (On, Off, On)	West Wall	≥0.05 V/in	230 (70)	787 (240)	1,017 (310)
11 (Feb 12th)	A (On, Off, On)	East Wall	≥0.05 V/in	198 (60)	787 (240)	985 (300)
12 (Feb 12th)	A (On, Off, On)	Center	≥0.05 V/in	214 (65)	787 (240)	1,001 (305)
	A (On, Off, On)	**Greatest extent**	≥0.05 V/in	**263 (80)**	**754 (230)**	**1017 (310)**
13 (Feb 12th)	C (On, Off, On)	East Wall	≥0.05 V/in	214 (65)	787 (240)	1,001 (305)
14 (Feb 12th)	C (On, Off, On)	West Wall	≥0.05 V/in	263 (80)	754 (230)	1,017 (310)
15 (Feb 12th)	C (On, Off, On)	Center	≥0.05 V/in	263 (80)	754 (230)	1,017 (310)
16 (Feb 12th)	C (On, Off, On)	West Wall	≥0.05 V/in	198 (60)	803 (245)	1,001 (305)
17 (Feb 12th)**	C (On, Off, On)	East Wall	≥0.05 V/in	-	-	-
18 (Feb 12th)**	C (On, Off, On)	Center	≥0.05 V/in	-	-	-
	C (On, Off, On)	**Greatest extent**	≥0.05 V/in	**263 (80)**	**754 (230)**	**1,017 (310)**
19 (Feb 12th)	C (On, On, On)	Center	≥0.05 V/in	197 (60)	804 (245)	1,001 (305)
		Greatest extent	≥0.05 V/in	**197 (60)**	**804 (245)**	**1,001 (305)**
8 (June 14th)	E (On, Off, On)	East Wall	≥0.05 V/in	295 (90)	738 (225)	1033 (315)
9 (June 14th)	E (On, Off, On)	West Wall	≥0.05 V/in	262 (80)	771 (235)	1033 (315)
10 (June 14th)	E (On, Off, On)	Center	≥0.05 V/in	279 (85)	755 (230)	1033 (315)
11 (June 14th)	E (On, Off, On)	West Wall	≥0.05 V/in	262 (80)	771 (235)	1033 (315)
12 (June 14th)	E (On, Off, On)	East Wall	≥0.05 V/in	279 (85)	755 (230)	1033 (315)
13 (June 14th)	E (On, Off, On)	Center	≥0.05 V/in	279 (85)	755 (230)	1033 (315)
	E (On, Off, On)	**Greatest Extent**	≥0.05 V/in	**295 (90)**	**738 (225)**	**1033 (315)**
14 (June 14th)	F (On, Off, On)	East Wall	≥0.05 V/in	312 (95)	722 (220)	1033 (315)
15 (June 14th)	F (On, Off, On)	West Wall	≥0.05 V/in	344 (105)	771 (235)	1115 (340)
17 (June 14th)	F (On, Off, On)	West Wall	≥0.05 V/in	262 (80)	771 (235)	1033 (315)
18 (June 14th)	F (On, Off, On)	East Wall	≥0.05 V/in	279 (85)	755 (230)	1033 (315)
19 (June 14th)	F (On, Off, On)	Center	≥0.05 V/in	262 (80)	771 (235)	1033 (315)

Run (Date)	Pulser (Parasitic) Configuration	Location	Voltage Gradient	Range in ft (m)	Downstream Distance with respect to IIB in ft (m)*	Upstream Distance with respect to IIB in ft (m)*
26 (June 14th)	F (On, Off, On)	East Wall	≥0.05 V/in	279 (85)	755 (230)	1033 (315)
27 (June 14th)	F (On, Off, On)	West Wall	≥0.05 V/in	246 (75)	771 (235)	1017 (310)
28 (June 14th)	F (On, Off, On)	Center	≥0.05 V/in	262 (80)	771 (235)	1033 (315)
29 (June 14th)	F (On, Off, On)	West Wall	≥0.05 V/in	262 (80)	771 (235)	1033 (315)
30 (June 14th)	F (On, Off, On)	East Wall	≥0.05 V/in	312 (95)	722 (220)	1033 (315)
31 (June 14th)	F (On, Off, On)	Center	≥0.05 V/in	262 (80)	771 (235)	1033 (315)
	F (On, Off, On)	**Greatest Extent**	≥0.05 V/in	**344 (105)**	**771 (235)**	**1115 (340)**
1 (Feb 11th)	B (Off, Off, Off)	East Wall	≥0.03 V/in	2052 (625)	-903 (-275)***	1149 (350)
2 (Feb 11th)	B (Off, Off, Off)	West Wall	≥0.03 V/in	2052 (625)	-903 (-275)***	1149 (350)
3 (Feb 11th)	B (Off, Off, Off)	Center	≥0.03 V/in	2084 (635)	-919 (-280)***	1165 (355)
4 (Feb 11th)**	B (Off, Off, Off)	West Wall	≥0.03 V/in	**	**	**
5 (Feb 11th)	B (Off, Off, Off)	West Wall	≥0.03 V/in	2068 (630)	-919 (-280)***	1149 (350)
6 (Feb 11th)	B (Off, Off, Off)	East Wall	≥0.03 V/in	2019 (615)	-919 (-280)***	1100 (335)
7 (Feb 11th)	B (Off, Off, Off)	Center	≥0.03 V/in	2068 (630)	-919 (-280)***	1149 (350)
	B (Off, Off, Off)	**Greatest Extent**	≥0.03 V/in	**2084 (635)**	**-919 (-280)*** **	**1165 (355)**
8 (Feb 11th)	B (On, Off, On)	Center	≥0.03 V/in	542 (165)	640 (195)	1182 (360)
9 (Feb 11th)	B (On, Off, On)	East Wall	≥0.03 V/in	492 (150)	657 (200)	1149 (350)
10 (Feb 11th)	B (On, Off, On)	West Wall	≥0.03 V/in	476 (145)	689 (210)	1165 (355)
11 (Feb 11th)	B (On, Off, On)	Center	≥0.03 V/in	2017 (615)	-886 (-270)***	1131 (345)
12 (Feb 11th)	B (On, Off, On)	West Wall	≥0.03 V/in	442 (135)	689 (210)	1131 (345)
13 (Feb 11th)	B (On, Off, On)	East Wall	≥0.03 V/in	492 (150)	657 (200)	1149 (350)
	B (On, Off, On)	**Greatest Extent**	≥0.03 V/in	**2068 (630)**	**-886 (-270)*** **	**1182 (360)**
14 (Feb 11th)	B (On, On, On)	West Wall	≥0.03 V/in	442 (135)	689 (210)	1131 (345)
15 (Feb 11th)	B (On, On, On)	East Wall	≥0.03 V/in	492 (150)	657 (200)	1149 (350)
16 (Feb 11th)	B (On, On, On)	Center	≥0.03 V/in	443 (135)	706 (215)	1149 (350)
17 (Feb 11th)	B (On, On, On)	East Wall	≥0.03 V/in	607 (185)	558 (170)	1165 (355)
18 (Feb 11th)**	B (On, On, On)	West Wall	≥0.03 V/in	**	**	**
19 (Feb 11th)	B (On, On, On)	Center	≥0.03 V/in	492 (150)	673 (205)	1165 (355)
	B (On, On, On)	**Greatest extent**	≥0.03 V/in	**607 (185)**	**558 (170)**	**1165 (355)**

Run (Date)	Pulser (Parasitic) Configuration	Location	Voltage Gradient	Range in ft (m)	Downstream Distance with respect to IIB in ft (m)*	Upstream Distance with respect to IIB in ft (m)*
1 (Feb 12th)	D (On, On, Off)	East Wall	≥0.03 V/in	443 (135)	706 (215)	1149 (350)
2 (Feb 12th)	D (On, On, Off)	West Wall	≥0.03 V/in	443 (135)	706 (215)	1149 (350)
3 (Feb 12th)	D (On, On, Off)	Center	≥0.03 V/in	509 (155)	673 (205)	1182 (360)
4 (Feb 12th)	D (On, On, Off)	West Wall	≥0.03 V/in	442 (135)	689 (210)	1131 (345)
5 (Feb 12th)	D (On, On, Off)	East Wall	≥0.03 V/in	542 (165)	640 (195)	1182 (360)
6 (Feb 12th)	D (On, On, Off)	Center	≥0.03 V/in	460 (140)	689 (210)	1149 (350)
	D (On, On, Off)	**Greatest extent**	≥0.03 V/in	**542 (165)**	**640 (195)**	**1182 (360)**
7 (Feb 12th)	A (On, Off, On)	East Wall	≥0.03 V/in	492 (150)	657 (200)	1149 (350)
8 (Feb 12th)	A (On, Off, On)	West wall	≥0.03 V/in	425 (130)	706 (215)	1131 (345)
9 (Feb 12th)	A (On, Off, On)	Center	≥0.03 V/in	556 (170)	575 (175)	1131 (345)
10 (Feb 12th)	A (On, Off, On)	West Wall	≥0.03 V/in	442 (135)	689 (210)	1131 (345)
11 (Feb 12th)	A (On, Off, On)	East Wall	≥0.03 V/in	491 (155)	640 (195)	1131 (345)
12 (Feb 12th)	A (On, Off, On)	Center	≥0.03 V/in	671 (205)	460 (140)	1131 (345)
	A (On, Off, On)	**Greatest extent**	≥0.03 V/in	**689 (210)**	**460 (140)**	**1149 (350)**
13 (Feb 12th)	C (On, Off, On)	East Wall	≥0.03 V/in	474 (145)	657 (200)	1131 (345)
14 (Feb 12th)	C (On, Off, On)	West Wall	≥0.03 V/in	574 (175)	591 (180)	1165 (355)
15 (Feb 12th)	C (On, Off, On)	Center	≥0.03 V/in	542 (165)	607 (185)	1149 (350)
16 (Feb 12th)	C (On, Off, On)	West Wall	≥0.03 V/in	427 (130)	689 (210)	1116 (340)
17 (Feb 12th)	C (On, Off, On)	East Wall	≥0.03 V/in	**	**	**
18 (Feb 12th)	C (On, Off, On)	Center	≥0.03 V/in	**	**	**
	C (On, Off, On)	**Greatest extent**	≥0.03 V/in	**574 (175)**	**591 (180)**	**1165 (355)**
19 (Feb 12th)	C (On, On, On)	Center	≥0.03 V/in	458 (140)	673 (205)	1131 (345)
		Greatest extent	≥0.03 V/in	**458 (140)**	**673 (205)**	**1131 (345)**
8 (June 14th)	E (On, Off, On)	East Wall	≥0.03 V/in	492 (150)	673 (205)	1165 (355)
9 (June 14th)	E (On, Off, On)	West Wall	≥0.03 V/in	443 (135)	689 (210)	1132 (345)
10 (June 14th)	E (On, Off, On)	Center	≥0.03 V/in	459 (140)	673 (205)	1132 (345)
11 (June 14th)	E (On, Off, On)	West Wall	≥0.03 V/in	459 (140)	689 (210)	1148 (350)
12 (June 14th)	E (On, Off, On)	East Wall	≥0.03 V/in	459 (140)	673 (205)	1132 (345)
13 (June 14th)	E (On, Off, On)	Center	≥0.03 V/in	476 (145)	656 (200)	1132 (345)

Run (Date)	Pulser (Parasitic) Configuration	Location	Voltage Gradient	Range in ft (m)	Downstream Distance with respect to IIB in ft (m)*	Upstream Distance with respect to IIB in ft (m)*
	E (On, Off, On)	**Greatest Extent**	≥0.03 V/in	**492 (150)**	**673 (205)**	**1165 (355)**
14 (June 14th)	F (On, Off, On)	East Wall	≥0.03 V/in	525 (160)	623 (190)	1148 (350)
15 (June 14th)	F (On, Off, On)	West Wall	≥0.03 V/in	427 (130)	705 (215)	1132 (345)
17 (June 14th)	F (On, Off, On)	West Wall	≥0.03 V/in	410 (125)	705 (215)	1115 (340)
18 (June 14th)	F (On, Off, On)	East Wall	≥0.03 V/in	492 (150)	656 (200)	1148 (350)
19 (June 14th)	F (On, Off, On)	Center	≥0.03 V/in	427 (130)	689 (210)	1115 (350)
26 (June 14th)	F (On, Off, On)	East Wall	≥0.03 V/in	492 (150)	656 (200)	1148 (350)
27 (June 14th)	F (On, Off, On)	West Wall	≥0.03 V/in	410 (125)	722 (220)	1132 (345)
28 (June 14th)	F (On, Off, On)	Center	≥0.03 V/in	443 (135)	689 (210)	1132 (345)
29 (June 14th)	F (On, Off, On)	West Wall	≥0.03 V/in	410 (125)	705 (215)	1115 (350)
30 (June 14th)	F (On, Off, On)	East Wall	≥0.03 V/in	459 (140)	656 (200)	1115 (350)
31 (June 14th)	F (On, Off, On)	Center	≥0.03 V/in	410 (125)	705 (215)	1115 (350)
	F (On, Off, On)	**Greatest Extent**	≥0.03 V/in	**525 (160)**	**623 (190)**	**1148 (350)**

* Distances are from a zero point at the center of Barrier IIB's narrow array. This point is shown on Figure 3.

** Electric field measurements not included due to lack of GPS measurements.

*** Range of harmful effects extends from south of Barrier IIA to north of Barrier I, there is no safe zone between barriers.

Table 5. Pulser settings and target in-water field strengths for each test configuration.

Pulser Configuration	t_p (for energy calculation) ms	Barrier 2A Narrow			Barrier 2A Wide			Barrier 2B Narrow			Barrier 2B Wide			Barrier 1		
		V/in	ms	Hz	V/in	ms	Hz	V/in	ms	Hz	V/in	ms	Hz	V/in	ms	Hz
Alpha (A)	6.5	2.0	6.5	15	1.0	6.5	15	2.3	2.5	30	1.0	2.5	30	1.0	4.0	5
Bravo (B)	2.5	2.3	2.5	30	1.0	2.5	30	2.3	2.5	30	1.0	2.5	30	1.0	4.0	5
Charlie (C)	6.5	2.0	6.5	15	1.0	6.5	15	2.0	6.5	15	1.0	6.5	15	1.0	4.0	5
Delta (D)	2.5	2.3	2.5	30	1.0	2.5	30	OFF			OFF			1.0	4.0	5
Echo (E)	2.5	OFF			OFF			2.3	2.5	30	1.0	2.5	30	1.0	4.0	5
Foxtrot (F)	6.5	OFF			OFF			2.0	6.5	15	1.0	6.5	15	1.0	4.0	5

Table 6. Test results for sparking potential during fleeting operations.

Time	Barge Configuration	Pulser Configuration	Parasitic 1	Parasitic 2	Parasitic 3	Peak Voltage (Volts)	Peak Short Circuit Current (Amps)	Estimated Energy (mJoules)	Sparking Observed
08:10	Series	A	On	On	On	4.8			
08:12	Series	A	On	On	On	7.3			
08:13	Series	A	On	On	On	7.3		44.8	
08:15	Series	A	On	On	On		1.2		
08:17	Series	A	On	On	On		1.0		
08:18	Series	A	On	On	On		1.0		
08:20	Series	A	On	Off	On		1.5		
08:21	Series	A	On	Off	On		1.5		
08:23	Series	A	On	Off	On		1.4	62.6	
08:24	Series	A	On	Off	On	6.6			
08:25	Series	A	On	Off	On	7.4			
08:27	Series	A	On	Off	On	5.7			
08:35	Series	B	On	Off	On	8.7			
08:37	Series	B	On	Off	On	6.5			
08:38	Series	B	On	Off	On	9.9		33.5	
08:40	Series	B	On	Off	On		1.3		
08:42	Series	B	On	Off	On		1.8		
08:43	Series	B	On	Off	On		1.7		
08:47	Series	B	On	On	On		0.9		
08:48	Series	B	On	On	On		1.1		
08:50	Series	B	On	On	On		0.8	17.0	
08:52	Series	B	On	On	On	5.2			
08:53	Series	B	On	On	On	8.5			
08:56	Series	B	On	On	On	8.0			
09:06	Series	C	On	On	On	7.3			
09:07	Series	C	On	On	On	6.2			
09:09	Series	C	On	On	On	4.4		29.5	

Time	Barge Configuration	Pulser Configuration	Parasitic 1	Parasitic 2	Parasitic 3	Peak Voltage (Volts)	Peak Short Circuit Current (Amps)	Estimated Energy (mJoules)	Sparking Observed
09:12	Series	C	On	On	On		0.9		
09:14	Series	C	On	On	On		0.7		
09:16	Series	C	On	On	On		0.7		
09:22	Series	C	On	Off	On		1.5		
09:23	Series	C	On	Off	On		1.6		
09:25	Series	C	On	Off	On		1.5	81.7	
09:27	Series	C	On	Off	On	9.7			
09:29	Series	C	On	Off	On	7.7			
09:30	Series	C	On	Off	On	7.1			
09:37	Series	D	On	On	Off	4.4			
09:39	Series	D	On	On	Off	4.5			
09:40	Series	D	On	On	Off	4.3		2.9	
09:42	Series	D	On	On	Off		0.3		
09:43	Series	D	On	On	Off		0.3		YES
09:45	Series	D	On	On	Off		0.3		
09:56*	Series	E	On	Off	On		0.1		
10:00*	Series	E	On	Off	On	1.0		1.3	
15:34*	Series	E	On	Off	On	3.0			
15:39*	Series	E	On	Off	On		0.4		
09:43*	Series	F	On	Off	On	0.6			
09:45*	Series	F	On	Off	On	0.6			
09:48*	Series	F	On	Off	On		0.1	1.6	
09:52*	Series	F	On	Off	On		0.1		
15:21*	Series	F	On	Off	On		0.4		
15:28*	Series	F	On	Off	On	2.4			
10:25	Parallel	D	On	On	Off	1.6			
10:25	Parallel	D	On	On	Off	1.8			
10:27	Parallel	D	On	On	Off	1.5		0.7	

Time	Barge Configuration	Pulser Configuration	Parasitic 1	Parasitic 2	Parasitic 3	Peak Voltage (Volts)	Peak Short Circuit Current (Amps)	Estimated Energy (mJoules)	Sparking Observed
10:28	Parallel	D	On	On	Off		0.2		
10:29	Parallel	D	On	On	Off		0.2		
10:30	Parallel	D	On	On	Off		0.2		
10:36	Parallel	C	On	On	On		0.4		
10:38	Parallel	C	On	On	On		0.4		
10:39	Parallel	C	On	On	On		0.3	6.6	
10:40	Parallel	C	On	On	On	2.2			
10:41	Parallel	C	On	On	On	2.3			
10:42	Parallel	C	On	On	On	3.3			
10:48	Parallel	C	On	Off	On	2.4			
10:49	Parallel	C	On	Off	On	3.0			
10:51	Parallel	C	On	Off	On	2.9		11.0	
10:53	Parallel	C	On	Off	On		0.6		
10:53	Parallel	C	On	Off	On		0.7		
10:55	Parallel	C	On	Off	On		0.6		
13:19	Parallel	A	On	On	On	2.1			
13:20	Parallel	A	On	On	On	1.9			
13:21	Parallel	A	On	On	On	2.9		4.7	
13:25	Parallel	A	On	On	On		0.3		
13:26	Parallel	A	On	On	On		0.3		
13:27	Parallel	A	On	On	On		0.3		
13:29	Parallel	A	On	Off	On		0.4		
13:30	Parallel	A	On	Off	On		0.3		
13:31	Parallel	A	On	Off	On		0.4		
13:33	Parallel	A	On	Off	On		0.4	8.0	
13:34	Parallel	A	On	Off	On	2.7			
13:35	Parallel	A	On	Off	On	3.3			
13:37	Parallel	A	On	Off	On	3.6			

Time	Barge Configuration	Pulser Configuration	Parasitic 1	Parasitic 2	Parasitic 3	Peak Voltage (Volts)	Peak Short Circuit Current (Amps)	Estimated Energy (mJoules)	Sparking Observed
13:42	Parallel	B	On	Off	On	2.6			
13:43	Parallel	B	On	Off	On	2.5			
13:44	Parallel	B	On	Off	On	2.4		2.6	
13:46	Parallel	B	On	Off	On		0.4		
13:47	Parallel	B	On	Off	On		0.4		
13:49	Parallel	B	On	Off	On		0.4		
13:51	Parallel	B	On	On	On		0.3		
13:53	Parallel	B	On	On	On		0.3		
13:54	Parallel	B	On	On	On		0.3	1.8	
13:57	Parallel	B	On	On	On	2.6			
13:58	Parallel	B	On	On	On	2.6			
13:59	Parallel	B	On	On	On	2.2			
13:50*	Parallel	E	On	Off	On	0.6		0.2	
13:54*	Parallel	E	On	Off	On		0.1		
13:34*	Parallel	F	On	Off	On	0.5			
13:37*	Parallel	F	On	Off	On		0.1	0.3	
13:41*	Parallel	F	On	Off	On		0.1		
13:44*	Parallel	F	On	Off	On	0.4			
15:24	Insertion	D	On	On	Off	1.0			
15:25	Insertion	D	On	On	Off	1.8			
15:26	Insertion	D	On	On	Off	1.9		0.9	
15:28	Insertion	D	On	On	Off		0.2		
15:29	Insertion	D	On	On	Off		0.3		
15:37	Insertion	D	On	On	Off		0.2		
15:44	Insertion	C	On	On	On	7.1			YES
15:46	Insertion	C	On	On	On	4.7			YES
15:48	Insertion	C	On	On	On	4.7		34.4	YES
15:51	Insertion	C	On	On	On		1.1		

Time	Barge Configuration	Pulser Configuration	Parasitic 1	Parasitic 2	Parasitic 3	Peak Voltage (Volts)	Peak Short Circuit Current (Amps)	Estimated Energy (mJoules)	Sparking Observed
15:53	Insertion	C	On	On	On		1.0		
15:55	Insertion	C	On	On	On		0.9		
15:58	Insertion	C	On	Off	On		3.3		
16:10	Insertion	C	On	Off	On		2.3		
16:11	Insertion	C	On	Off	On		1.8	132.0	YES
16:13	Insertion	C	On	Off	On	7.2			YES
16:16	Insertion	C	On	Off	On	9.7			YES
16:18	Insertion	C	On	Off	On	7.8			YES
16:24	Insertion	B	On	Off	On	6.2			
16:26	Insertion	B	On	Off	On	9.7			YES
16:28	Insertion	B	On	Off	On	10.0		35.5	YES
16:31	Insertion	B	On	Off	On		1.5		
16:33	Insertion	B	On	Off	On		1.4		
16:34	Insertion	B	On	Off	On		2.1		
16:37	Insertion	B	On	On	On		1.5		YES
16:38	Insertion	B	On	On	On		1.4		
16:39	Insertion	B	On	On	On		1.0	20.7	YES
16:41	Insertion	B	On	On	On	5.7			YES
16:42	Insertion	B	On	On	On	6.4			
16:44	Insertion	B	On	On	On	6.9			YES
16:49	Insertion	A	On	Off	On	5.5			
16:50	Insertion	A	On	Off	On	7.0			
16:52	Insertion	A	On	Off	On	8.1		75.9	YES
16:55	Insertion	A	On	Off	On		1.6		YES
16:56	Insertion	A	On	Off	On		1.6		YES
16:57	Insertion	A	On	Off	On		1.9		YES
17:02	Insertion	A	On	On	On		1.6		
17:04	Insertion	A	On	On	On		0.6		

Time	Barge Configuration	Pulser Configuration	Parasitic 1	Parasitic 2	Parasitic 3	Peak Voltage (Volts)	Peak Short Circuit Current (Amps)	Estimated Energy (mJoules)	Sparking Observed
17:05	Insertion	A	On	On	On		0.8	43.3	
17:07	Insertion	A	On	On	On	5.8			
17:08	Insertion	A	On	On	On	7.7			
17:09	Insertion	A	On	On	On	6.7			YES
14:24*	Insertion	E	On	Off	On		0.2	0.8	
14:28*	Insertion	E	On	Off	On	1.5			
14:46*	Insertion	F	On	Off	On	1.3		1.7	
14:51*	Insertion	F	On	Off	On		0.2		

*All data taken 5 February 2011 except rows denoted with an asterisk (*), which were taken 15 June 2011.

Table 7. Test results for sparking potential during collision simulations.

Time	Pulser Configuration	Parasitic 1	Parasitic 2	Parasitic 3	Peak Voltage (Volts)	Peak Short Circuit Current (Amps)	Estimated Energy (mJoules)	Sparking Observed
09:06	A	On	On	On	68.6			YES
09:08	A	On	On	On	78.4			YES
09:09	A	On	On	On	72.8		5,667	YES
09:12	A	On	On	On		12.8		YES
09:13	A	On	On	On		11.9		YES
09:14	A	On	On	On		11.0		YES
09:16	A	On	Off	On		12.8		YES
09:17	A	On	Off	On		12.5		YES
09:18	A	On	Off	On		11.0	5,207	YES
09:20	A	On	Off	On	69.3			YES
09:21	A	On	Off	On	69.0			YES
09:23	A	On	Off	On	60.3			YES
09:29	B	On	Off	On	62.4			YES
09:30	B	On	Off	On	60.7			YES

Time	Pulser Configuration	Parasitic 1	Parasitic 2	Parasitic 3	Peak Voltage (Volts)	Peak Short Circuit Current (Amps)	Estimated Energy (mJoules)	Sparking Observed
09:31	B	On	Off	On	72.6		1,941	YES
09:33	B	On	Off	On		11.4		YES
09:35	B	On	Off	On		11.9		YES
09:36	B	On	Off	On		12.4		YES
09:40	B	On	On	On		11.4		YES
09:41	B	On	On	On		10.7		YES
09:43	B	On	On	On		11.4	1,973	YES
09:45	B	On	On	On	71.9			YES
09:46	B	On	On	On	72.7			YES
09:47	B	On	On	On	67.4			YES
09:53	C	On	On	On	85.9			YES
09:54	C	On	On	On	87.4			YES
09:55	C	On	On	On	96.3		12,033	YES
09:57	C	On	On	On		20.9		YES
09:58	C	On	On	On		20.3		YES
09:59	C	On	On	On		20.6		YES
10:03	C	On	Off	On		20.2		YES
10:05	C	On	Off	On		16.0		YES
10:06	C	On	Off	On		18.6	11,121	YES
10:08	C	On	Off	On	92.6			YES
10:10	C	On	Off	On	96.6			YES
10:11	C	On	Off	On	91.8			YES
10:30	D	On	On	Off	19.2			NO
10:33	D	On	On	Off	16.6			NO
10:34	D	On	On	Off	15.3		727	NO
10:40	D	On	On	Off		19.3		NO
10:42	D	On	On	Off		14.7		NO
10:44	D	On	On	Off		17.2		NO

Time	Pulser Configuration	Parasitic 1	Parasitic 2	Parasitic 3	Peak Voltage (Volts)	Peak Short Circuit Current (Amps)	Estimated Energy (mJoules)	Sparking Observed
N/A*	E	On	Off	On	62		2774	YES
N/A*	E	On	Off	On	35			YES
N/A*	E	On	Off	On		8.4		YES
N/A*	E	On	Off	On		9.2		YES
N/A*	F	On	Off	On	72		2581	YES
N/A*	F	On	Off	On	68			YES
N/A*	F	On	Off	On		13.5		YES
N/A*	F	On	Off	On		16		YES

*All data taken 7 February 2011 except rows denoted with an asterisk (*), which were taken 16 June 2011. Data acquisition times are not available for the 16 June data.

Notes for Tables 8–10.

V01 - Potential between south towboat and Barge 1
V12 - Potential between Barges 1 and 2
V23 - Potential between Barges 2 and 3
V34 - Potential between Barges 3 and 4
V45 - Potential between Barges 4 and 5
V56 - Potential between Barge 5 and north towboat
South Towboat on 8 Feb was the Joe Avery
North Towboat on 8 Feb was the Buster White
South Towboat on 10 Feb was the Jack Crowley
North Towboat on 10 Feb was the Buster White

Table 8. Test results for long tow traversing Barrier IIA, conducted on 8 and 10 February 2011.

Date Time	Pulser Configuration	Direction of Travel	Parasitic State			Barrier IIA Peak Potential Difference (volts)					
			1	2	3	V01	V12	V23	V34	V45	V56
8 Feb 09:50 – 10:10	A	Downstream	ON	ON	ON	2.23	2.11	2.06	2.09	1.60	18.66
8 Feb 10:26 – 10:51	A	Upstream	ON	ON	ON	2.22	2.07	2.77	2.41	1.65	18.67
8 Feb 13:40 – xxx	A	Aborted	ON	ON	ON	—	—	—	—	—	—
8 Feb 14:00 – 14:23	A	Upstream	ON	ON	ON	2.67	2.08	3.23	2.39	1.70	20.44
8 Feb 14:27 – 14:41	A	Downstream	ON	OFF	ON	2.47	1.98	1.75	3.04	2.10	21.50
8 Feb 14:43 – 15:00	A	Upstream	ON	OFF	ON	2.42	2.00	3.45	2.75	1.93	19.99
8 Feb 15:05 – 15:18	A	Downstream	ON	OFF	ON	2.38	2.44	2.40	2.49	1.26	18.08
8 Feb 15:23 – 15:41	B	Upstream	ON	OFF	ON	2.59	2.34	2.65	3.10	1.45	25.34

Date Time	Pulser Configuration	Direction of Travel	Parasitic State			Barrier IIA Peak Potential Difference (volts)					
			1	2	3	V01	V12	V23	V34	V45	V56
8 Feb 15:44 – 16:00	B	Downstream	ON	OFF	ON	2.65	2.28	3.40	2.22	2.18	22.97
8 Feb 16:01 – 16:17	B	Upstream	ON	OFF	ON	2.52	2.07	2.90	2.97	1.97	22.35
8 Feb 16:21 – 16:37	B	Downstream	ON	ON	ON	4.14	2.48	5.22	4.95	2.03	23.21
8 Feb 16:39 – 16:59	B	Upstream	ON	ON	ON	2.82	2.17	1.70	4.01	1.62	22.84
10 Feb 08:41 – 08:59	B	Downstream	ON	ON	ON	29.69	1.74	3.46	1.84	1.31	21.47
10 Feb 09:16 – 09:34	C	Upstream	ON	ON	ON	26.41	1.68	1.45	2.35	1.09	18.25
10 Feb 09:35 – 09:48	C	Downstream	ON	ON	ON	28.55	1.81	2.93	2.42	1.49	20.42
10 Feb 09:52 – 10:08	C	Upstream	ON	ON	ON	30.30	1.92	1.51	2.76	1.59	19.86
10 Feb 10:10 – 10:25	C	Downstream	ON	OFF	ON	27.85	2.57	1.78	2.48	1.22	19.40
10 Feb 10:26 – 10:42	C	Upstream	ON	OFF	ON	27.83	3.02	2.09	2.38	1.28	19.89
10 Feb 13:13 – 13:27	C	Downstream	ON	OFF	ON	28.34	1.68	4.36	2.62	1.46	21.49
10 Feb 13:30 – 13:48	D	Upstream	ON	ON	OFF	33.11	2.59	4.64	2.15	1.83	23.60
10 Feb 13:49 – 14:02	D	Downstream	ON	ON	OFF	30.73	2.07	3.38	2.08	1.68	21.81
10 Feb 14:02 – 14:16	D	Upstream	ON	ON	OFF	30.90	1.91	3.85	2.31	1.47	21.84

Table 9. Test results for long tow traversing Barrier IIB, conducted on 8 and 10 February 2011.

Date Time	Pulser Configuration	Direction of Travel	Parasitic State			Barrier IIB Peak Potential Difference (volts)					
			1	2	3	V01	V12	V23	V34	V45	V56
8 Feb 09:50 – 10:10	A	Downstream	ON	ON	ON	3.01	2.44	4.55	2.60	1.92	25.55
8 Feb 10:26 – 10:51	A	Upstream	ON	ON	ON	2.91	1.94	3.77	4.23	1.93	26.92
8 Feb 13:40 – xxx	A	Aborted	ON	ON	ON	—	—	—	—	—	—
8 Feb 14:00 – 14:23	A	Upstream	ON	ON	ON	3.31	3.16	3.70	3.65	1.96	27.16
8 Feb 14:27 – 14:41	A	Downstream	ON	OFF	ON	3.26	3.24	3.09	2.33	1.76	29.08
8 Feb 14:43 – 15:00	A	Upstream	ON	OFF	ON	3.24	2.65	4.61	2.90	1.71	28.70
8 Feb 15:05 – 15:18	A	Downstream	ON	OFF	ON	3.24	2.55	3.13	3.90	1.41	27.07
8 Feb 15:23 – 15:41	B	Upstream	ON	OFF	ON	2.89	2.17	4.56	2.58	2.26	26.47
8 Feb 15:44 – 16:00	B	Downstream	ON	OFF	ON	3.50	2.34	2.96	2.56	1.86	28.74
8 Feb 16:01 – 16:17	B	Upstream	ON	OFF	ON	2.92	2.35	4.40	2.81	2.49	29.08
8 Feb 16:21 – 16:37	B	Downstream	ON	ON	ON	4.94	2.97	5.99	3.34	2.76	32.90
8 Feb 16:39 – 16:59	B	Upstream	ON	ON	ON	2.80	2.53	4.76	4.70	2.17	26.56
10 Feb 08:41 – 08:59	B	Downstream	ON	ON	ON	35.14	2.02	2.82	4.96	1.37	26.95
10 Feb 09:16 – 09:34	C	Upstream	ON	ON	ON	34.63	1.90	4.29	2.71	1.34	24.17

Date Time	Pulser Configuration	Direction of Travel	Parasitic State			Barrier IIB Peak Potential Difference (volts)					
10 Feb 09:35 – 09:48	C	Downstream	ON	ON	ON	34.61	1.99	2.71	1.81	1.77	27.09
10 Feb 09:52 – 10:08	C	Upstream	ON	ON	ON	35.42	2.18	2.39	3.62	1.40	24.55
10 Feb 10:10 – 10:25	C	Downstream	ON	OFF	ON	33.93	3.09	3.50	3.00	2.20	27.98
10 Feb 10:26 – 10:42	C	Upstream	ON	OFF	ON	36.62	3.57	3.81	1.87	1.83	25.12
10 Feb 13:13 – 13:27	C	Downstream	ON	OFF	ON	33.06	2.03	2.01	2.16	1.72	25.55
10 Feb 13:30 – 13:48	D	Upstream	ON	ON	OFF	—	—	—	—	—	—
10 Feb 13:49 – 14:02	D	Downstream	ON	ON	OFF	—	—	—	—	—	—
10 Feb 14:02 – 14:16	D	Upstream	ON	ON	OFF	—	—	—	—	—	—

Table 10. Test results for long tow traversing Barrier I, conducted on 8 and 10 February 2011.

Date Time	Pulser Configuration	Direction of Travel	Parasitic State			Barrier I Peak Potential Difference (volts)					
			1	2	3	V01	V12	V23	V34	V45	V56
8 Feb 09:50 – 10:10	A	Downstream	ON	ON	ON	0.90	0.77	0.57	0.90	0.44	7.40
8 Feb 10:26 – 10:51	A	Upstream	ON	ON	ON	0.83	0.62	0.97	0.91	0.59	7.54
8 Feb 13:40 – xxx	A	Aborted	ON	ON	ON	—	—	—	—	—	—
8 Feb 14:00 – 14:23	A	Upstream	ON	ON	ON	0.82	0.64	1.04	1.33	0.90	7.80
8 Feb 14:27 – 14:41	A	Downstream	ON	OFF	ON	0.90	0.64	0.86	0.71	0.81	7.55
8 Feb 14:43 – 15:00	A	Upstream	ON	OFF	ON	0.79	0.56	1.20	0.80	0.83	8.27
8 Feb 15:05 – 15:18	A	Downstream	ON	OFF	ON	0.87	0.96	0.84	0.95	0.39	7.51
8 Feb 15:23 – 15:41	B	Upstream	ON	OFF	ON	0.85	0.64	1.37	0.62	0.36	7.52
8 Feb 15:44 – 16:00	B	Downstream	ON	OFF	ON	0.88	0.67	1.70	0.65	0.55	7.95
8 Feb 16:01 – 16:17	B	Upstream	ON	OFF	ON	0.79	0.61	0.67	0.67	0.61	7.38
8 Feb 16:21 – 16:37	B	Downstream	ON	ON	ON	1.24	0.65	0.70	0.99	0.79	9.91
8 Feb 16:39 – 16:59	B	Upstream	ON	ON	ON	0.77	0.62	1.11	0.93	0.57	7.60
10 Feb 08:41 – 08:59	B	Downstream	ON	ON	ON	10.14	0.55	1.14	0.72	0.79	7.43
10 Feb 09:16 – 09:34	C	Upstream	ON	ON	ON	11.46	1.04	1.55	0.69	0.44	7.76

Date Time	Pulser Configuration	Direction of Travel	Parasitic State			Barrier I Peak Potential Difference (volts)					
			1	2	3	V01	V12	V23	V34	V45	V56
10 Feb 09:35 – 09:48	C	Downstream	ON	ON	ON	11.48	0.60	0.76	0.82	0.39	8.04
10 Feb 09:52 – 10:08	C	Upstream	ON	ON	ON	9.82	0.59	1.17	0.82	0.56	7.35
10 Feb 10:10 – 10:25	C	Downstream	ON	OFF	ON	10.86	0.73	0.89	0.67	0.52	7.63
10 Feb 10:26 – 10:42	C	Upstream	ON	OFF	ON	9.72	0.67	0.80	0.79	0.53	7.31
10 Feb 13:13 – 13:27	C	Downstream	ON	OFF	ON	10.76	0.61	1.30	0.63	0.50	7.28
10 Feb 13:30 – 13:48	D	Upstream	ON	ON	OFF	10.25	1.19	1.21	0.67	0.53	7.76
10 Feb 13:49 – 14:02	D	Downstream	ON	ON	OFF	11.56	0.72	0.75	0.90	0.54	7.90
10 Feb 14:02 – 14:16	D	Upstream	ON	ON	OFF	10.70	0.73	0.54	0.78	0.61	7.98

Table 11. Test results for bollard voltage potential and 500-ohm current tests at fleeting area.

Time	Pulser Configuration	Parasitic 1	Parasitic 2	Parasitic 3	Bollard 2 Peak Voltage (Volts)	Bollard 3 Peak Voltage (Volts)	Bollard 2 Peak 500 Ω Current (mAmps)	Bollard 3 Peak 500 Ω Current (mAmps)
14:09 – 14:10	B	On	Off	On	10.8	4.9		
14:12 – 14:13	B	On	Off	On			16.0	6.7
14:16 – 14:18	B	On	Off	On			17.0	7.4
14:19 – 14:21	B	On	Off	On	9.2	4.7		
14:28 – 14:30	B	On	On	On	7.2	3.0		
14:31 – 14:33	B	On	On	On			11.3	5.1
14:51 – 14:54	A	On	On	On			11.7	4.3
14:55 – 14:57	A	On	On	On	6.3	3.0		
14:58 – 15:00	A	On	Off	On	7.9	3.8		
15:01 – 15:03	A	On	Off	On			15.4	10.7
15:06 – 15:08	C	On	Off	On			14.7	8.1
15:09 – 15:11	C	On	Off	On	11.2	7.9		
15:13 – 15:15	C	On	On	On	6.9	4.3		
15:16 – 15:18	C	On	On	On			12.7	7
15:21 – 15:23	D	On	On	Off			5.9	3.4
15:24 – 15:26	D	On	On	Off	3.0	1.6		
10:36 – 10:37*	F	On	Off	On	1.1	0.7		
10:38 – 10:39*	F	On	Off	On			2.0	1.4
15:59 – 16:00*	E	On	Off	On	3.3	2.3		
10:36 – 10:37*	F	On	Off	On	1.1	0.7		
10:38 – 10:39*	F	On	Off	On			2.0	1.4
15:59 –16:00*	E	On	Off	On	3.3	2.3		

*All data taken 7 February 2011 except rows denoted with an asterisk (*), which were taken 15 June 2011.

Table 12. Barge corrosion potential measurements taken with Cu/CuSo4 reference electrode, conducted on 5 February 2011.

Time	Measurement Location	Pulser Configuration	Potential (-mV)	Water Conductivity (µS/cm)
10:00	SE corner of north barge (just north of Bollard 3)	C	360	1590
14:00	SE corner of north barge (just north of Bollard 3)	B	380	1590

Table 13. General corrosion rates for steel in fresh water.
(Source: *Civil Engineering Corrosion Control, Volume 1 – Corrosion Control – General*, p 222.)

Potential between steel and Cu/CuSo4 reference electrode (-mV)		Corrosivity
Min	Max	
550	and up-	Severe
450	550	Moderate
150	450	Mild
and below	150	Unlikely

Note: Fresh water is defined as having either greater than 300 Ω-cm resistivity or less than 3300 µS/cm conductivity.

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[9] West, Lewis H. and Thomas F. Lewicki. January 1975. *Civil Engineering Corrosion Control, Volume 1 – Corrosion Control – General*. AFCEC-TR-74-6, Volume 1.

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Appendix A: Instrumentation and Data Reduction

Data acquisition equipment

A Pacific Instruments 6000 Series Data Acquisition System was used to continuously measure and record the voltage differentials. This system was chosen because of its multiple independent channel capabilities and its high sampling rate. The data acquisition system was connected to a laptop computer through a GPIB interface and the data was immediately transferred to the computer for storage. Because of the high sample rate and long scan times, barrier pulses were easily captured. When interpreting the Pacific data, the individual pulses and the ‘envelope’ (overall trend of the peak values) of the waveform may both be examined.

The Pacific Instruments 6000 Series Data Acquisition System is a high performance transducer signal conditioning, digitizing, and control system. The system is modular to accommodate applications of different size and transducer types. For this data collection, the Pacific Instruments Model 6033 8-channel strain gage transducer digitizing boards were used. These boards were configured for differential voltage measurements. The input to these boards has an impedance of 50 Megaohms shunted by 1000 picofarads. Measurements were taken using a sampling frequency of 8,000 samples/second for all testing. The unit has a 24-channel capability and the noise per channel is 200 microvolts (μV) peak-to-peak.

Tektronix P5200 High voltage Differential Probes were used to attenuate the voltage signal level at the input and to isolate the Pacific Instruments 6000. The Tektronix Differential Probe has a 25 megahertz (MHz) bandwidth and an input impedance of 4 Megaohms with a common mode rejection ration of 80 dB at 60 Hz. The maximum voltage input at the 1/50 attenuation setting is 130 V. The maximum voltage input at the 1/500 setting is 1300 V.

GPS data collection with Trimble GeoXH

Throughout the project all electrical measurements on moving vessels were referenced with geospatial coordinates to aid in mapping and determining the extent and nature of the electrical field. Global Positioning Systems (GPS) were used to record the data. A GPS was placed on the bow of the Boston Whaler and each towboat of the long tow. Maximum margins of error for GPS accuracy was +/- 0.1 meter. Data for testing runs that exceeded the minimal level accuracy were excluded from analysis.

The GPS recorded its position every two seconds. Because the data acquisition instruments recorded voltages at millisecond intervals, in order to georeference the electrical data a linear interpolation of the GPS data was required. The electrical measurements were georeferenced by using the barrier array as a marker. Because the maximum electrical measurement values occur over the barrier, the time values of the measurement files were georeferenced by synchronizing the time of the maximum values with the time of the location of the barrier arrays in the GPS files.

Data reduction

In order to match the electrical data with the georeference data, the electrical data was downloaded into Matlab, along with the georeference data. The georeference data was broken down by run into separate files. The known GPS coordinates for the center of Barrier IIA were matched up with the largest absolute voltage value contained within each run for the electrical data, and the electrical data for each run matched up with the GPS data for that run via the time logs for each data set. Because the electrical data contained far more readings per minute than the georeference data, linear interpolation was used to infer the GPS coordinates for the voltage readings which occurred between GPS readings, thus providing an approximate GPS position for each reading contained within the electrical data. These newly combined files were then saved according to run number.

Appendix B: Electric Hazard Analysis

Computation of hazardous electric field levels

The analysis of the effects of the measured voltages and electric field gradients and the resultant body current on a human immersed in the CSSC near the barriers is complex. While many studies of the effects of electrical shock to animals and humans are published in the scientific literature, almost all investigate bodies in air, not immersed in water, and with single current burst shocks from 50 to 60 Hz alternating current (AC). The same is true for electrical safety standards and codes. In addition, many continuously changing environmental and physiological variables characterize the situation (NEDU TR 08-01).

The Navy Experimental Diving Unit (NEDU) reviewed electric shock studies as well as appropriate electrical safety specifications and codes in the scientific literature to determine conservative, relevant physiological effects likely to occur in humans exposed to electric shock while immersed in the water, with water conductivity and electric field strengths over the range found in the CSSC (NEDU TR 08-01).

Following conservative methods and assumption, NEDU used measured field strength data, together with generally accepted body resistance values, to evaluate the maximum electrical body currents likely to be experienced by a person immersed in the CSSC. The safety and possible physiological effects of derived maximum body currents were evaluated using research studies available in the open scientific literature as well as national and international electrical safety specifications and codes (NEDU TR 08-01).

Time-current zones of physiological effects of a DC current pulse on a human body are shown in Figure B1 (reproduced from the IEC Publication 60479-1). The zones, current boundaries, and physiological effects are listed in Table B1. They indicate that to remain below the threshold of causing patho-physiological effects, such as cardiac arrest, breathing arrest, and burns or other cellular damage, may occur the current through the body must be ≤ 500 milliamperes (mA) DC for pulse widths less than 10 ms..

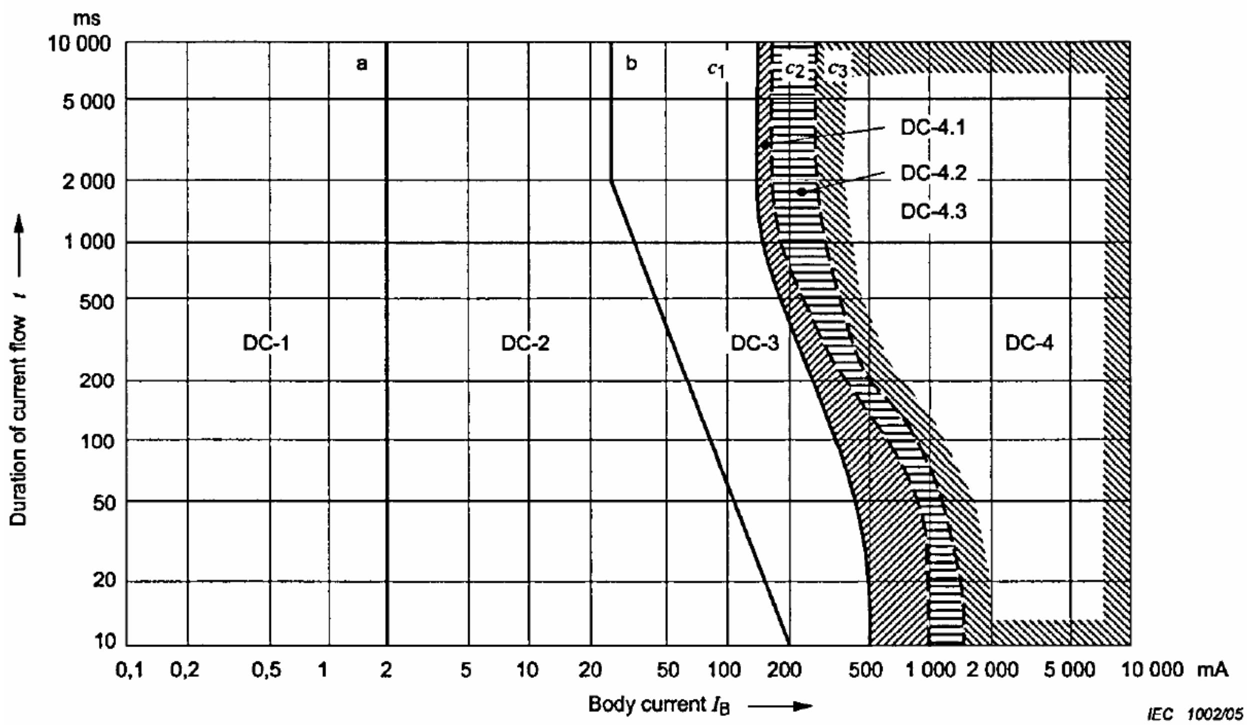

Figure B1. Time-Current Zones of Effects of DC Currents (figure 22 of IEC 60479-1).

Table B1. Time-current zones from Figure B1 for physiological effects of single-pulse DC Shock for hand-to-ft pathway. Source: IEC Publication 60479-1, Table 13.

Zones	Current Boundaries	Physiological Effects
DC-1	Up to 2.0 mA, Curve a	Slight pricking sensation possible when making, breaking or rapidly altering current flow.
DC-2	2.0 mA up to Curve b	Involuntary muscular contractions likely, especially when making, breaking or rapidly altering current flow but usually no harmful electrical physiological effects.
DC-3	Curve b & above	Strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart may occur, increasing with current magnitude and time. Usually no organic damage to be expected.
DC-4	Above Curve c1	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, & burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time.
	Between Curves c1 & c2	DC-4.1: Probability of ventricular fibrillation increasing up to about 5%
	Between Curves c2 & c3	DC-4.2: Probability of ventricular fibrillation increasing up to about 50%
	Beyond Curve c3	DC-4.3: Probability of ventricular fibrillation above 50%

The region where patho-physiological effects may occur is identified as region DC-4 in Figure B1. The minimum value of body current to pass into area DC-4 (the c_1 curve in Figure B1) is 500 mA for durations of current flow less than 10 ms. The c_1 curve appears to transition to vertical for pulse duration less than 10 ms, so the 500 mA value is valid for both Barrier I's 4 ms and Barrier II's 2.5 and 6.5 ms pulse widths.

Figure B1 and Table B1 can also be used to evaluate the current bursts induced by repetitive pulse shocks. However, the threshold for ventricular fibrillation applicable to the second current burst can be as low as 65% of the threshold current applicable to the first burst. Each succeeding pulse reduces the threshold current appropriate for the preceding burst for ventricular fibrillation by another ≈35%, until a minimum threshold of ≤10% of the single-pulse threshold is reached for ≥7 bursts. Since a person immersed in the CSSC near a fish barrier will experience 5 or 6.5 pulses per second for an indefinite period, the value of the threshold current appropriate for evaluating the risk for ventricular fibrillation posed to such a person is ≤10% of the threshold current for a single-pulse DC shock.[6] Reducing the threshold to 10% of the single-pulse current value (as is appropriate for the continuously repeated fish barrier pulses) dramatically changes the fibrillation threshold to a < 50 mA pulse for a <5% risk of fibrillation (c_1 curve, Figure A-1 and Table A-1).[7]

Therefore, to identify the areas in the CSSC where it is likely harmful to be immersed in the water, it is necessary to be able to calculate the areas where an immersed person would develop a current through the body greater than 50 mA. This can be done using the demagnetizing factors technique.

In a swimmer not wearing an insulating garment, current can flow into the person through all areas of the body's surface. In addition, the field within the body can be significantly altered from that which was in the volume of water before the body was immersed. The degree of alteration is strongly influenced by the relative electric resistivity of the water compared with that of the immersed body. ERA Technology Limited, Stoner, and Osborn present a technique that represents the body as an ellipsoid and calculates the ratio of the current density in the body to that in the water before the body is immersed. It solves the problem by "analogy with a corresponding magnetic problem, namely that of determining the magnetic flux density inside a magnetic ellipsoid when introduced into a uniform magnetic field.

[6] Ibid, page 38.

[7] Ibid, page 38.

Solutions to this problem are well known and expressed in terms of 'demagnetizing factors.'"[8]

The demagnetizing-factors technique reveals that the most severe physical orientation in low-resistivity (i.e., high-conductivity) water is that in which a person is upright, with the electric field oriented in the direction from chest to back (Case A). For high-resistivity (i.e., low-conductivity) water, the most severe exposure orientation occurs when a person's body is parallel to the water surface, with the direction of the field oriented along the body length (Case S).[9]

In order to determine the worst-case electric field value (minimum electric field strength that might produce harmful physiological effects), four combinations of worst-case resistivities and body orientations were analyzed.

Water conductivity data collected by the Metropolitan Water Reclamation District of Greater Chicago at CSSC river miles 304.7 and 296.2 from October 1998 – April 2010 were used in the analysis. Resistivity is the inverse of conductivity. Resistivity ranged from a minimum of 2.13 Ω-m to a maximum of 20.45 Ω-m, with a median value of 10.19 Ω-m. The transition from low to high resistivity occurs around 10 Ω-m. Therefore, the median value of 10.19 Ω-m could be considered either low (Case A) or high (Case S) resistivity, and was evaluated for each case.

The computation of the minimum electric field strength likely to cause harmful effects can be done using equations from the NEDU report "Evaluation of Risk That Electric Fish Barriers Pose to Human Immersion in the Chicago Sanitary and Ship Canal."

The variables used in the computations are:

- k –(water resistivity)/(body resistivity)
- I_b –current density in the body once it is immersed
- I_o –current density in the water before the body is immersed
- I_B –current produced through the chest area by body current density I_b
- ρ –resistivity
- E –electric field strength

[8] Ibid, pages 25-26.

[9] Ibid, page 26.

The assumptions used in the computations are:

1. Water resistivity(taken from October 1998 through April 2010 data)
   a. minimum value of 2.13 Ω-m
   b. median value of 10.19 Ω-m
   c. maximum value of 20.45 Ω-m
2. Body resistivity is 3.75 Ω-m[10]
3. Cross sectional area of chest is 0.08 m^2[11]
4. $I_B \leq 50$ mA (0.05 A) DC to avoid harmful effects (as explained above)

The computations for the four combinations of worst-case resistivities and body orientations for harmful physiological effects (zone DC-4 of Figure B1 and Table B1) are shown below. In these computations, references to equation numbers and pages refer to those items in the NEDU report. The results are summarized in Table B2. The lowest value where harmful effects are likely, and therefore the worst case, is approximately 0.05 V/in.

<u>Low Resistivity Case A</u>

k = 2.13 Ω-m / 3.75 Ω-m = 0.57	(Assumptions 1 and 2)
$(I_b/I_o) = k/(1+[k-1] \times 0.566)$	(Equation for Case A, page 26)
$(I_b/I_o) = 0.57/(1+[0.57-1] \times 0.566) = 0.75$	
$I_b = 0.75 \times I_o$	
$I_B = I_b \times 0.08\ m^2 = 0.75 \times I_o \times 0.08\ m^2 = 0.06\ m^2 \times I_o$	(Equation 2, page 27 and assumption 3)
$I_o = I_B/0.06\ m^2$	
$I_o \leq 0.05\ A/0.06\ m^2$	(Assumption 4)
$I_o \leq 0.833\ A/m^2$	
$E = I_o \times \rho$	(Equation page 39)

[10]Ibid, page 26.

[11] Ibid, page 27.

$E \leq 0.833\ A/m^2 \times 2.13\ \Omega\text{-m}$	(Assumption 1)
***E* ≤ 1.77 V/m (0.54 V/ft)**	Threshold for low resistivity Case A

<u>Midrange Resistivity Case A</u>

$k = 10.19\ \Omega\text{-m} / 3.75\ \Omega\text{-m} = 2.72$	(Assumptions 1 and 2)
$(I_b/I_o) = k/(1+[k-1] \times 0.566)$	(Equation for Case A, page 26)
$(I_b/I_o) = 2.72/(1+[2.72-1] \times 0.566) = 1.38$	
$I_b = 1.38 \times I_o$	
$I_B = I_b \times 0.08\ m^2 = 1.38 \times I_o \times 0.08\ m^2 = 0.11\ m^2 \times I_o$	(Equation 2, page 27 and assumption 3)
$I_o = I_B/0.11\ m^2$	
$I_o \leq 0.05\ A/0.11\ m^2$	(Assumption 4)
$I_o \leq 0.455\ A/m^2$	
$E = I_o \times \rho$	(Equation page 39)
$E \leq 0.455\ A/m^2 \times 10.19\ \Omega\text{-m}$	(Assumption 1)
***E* ≤ 4.64 V/m (1.41 V/ft)**	Threshold for midrange resistivity Case A

<u>Midrange Resistivity Case S</u>

$k = 10.19\ \Omega\text{-m} / 3.75\ \Omega\text{-m} = 2.72$	
$(I_b/I_o) = k/(1+[k-1] \times 0.034)$	(Equation for Case S, page 26)

$(I_b/I_o) = 2.72/(1+[2.72-1] \times 0.034) = 2.57$	
$I_b = 2.57 \times I_o$	
$I_B = I_b \times 0.08\ m^2 = 2.57 \times I_o \times 0.08\ m^2 = 0.21\ m^2 \times I_o$	(Equation 2, page 27 and assumption 3)
$I_o = I_B/0.21\ m^2$	
$I_o \leq 0.05\ A/0.21\ m^2$	(Assumption 4)
$I_o \leq 0.238\ A/m^2$	
$E = I_o \times \rho$	(Equation page 39)
$E \leq 0.238\ A/m^2 \times 10.19\ \Omega\text{-m}$	(Assumption 1)
***E* ≤ 2.43 V/m (0.74 V/ft)**	Threshold for midrange resistivity Case S

High Resistivity Case S

$k = 20.45\ \Omega\text{-m} / 3.75\ \Omega\text{-m} = 5.45$	
$(I_b/I_o) = k/(1+[k-1] \times 0.034)$	(Equation for Case S, page 26)
$(I_b/I_o) = 5.45/(1+[5.45-1] \times 0.034) = 4.73$	
$I_b = 4.73 \times I_o$	
$I_B = I_b \times 0.08\ m^2 = 4.73 \times I_o \times 0.08\ m^2 = 0.38\ m^2 \times I_o$	(Equation 2, page 27 and assumption 3)
$I_o = I_B/0.38\ m^2$	
$I_o \leq 0.05\ A/0.38\ m^2$	(Assumption 4)
$I_o \leq 0.132\ A/m^2$	
$E = I_o \times \rho$	(Equation page 39)

$E \leq 0.132\ A/m^2 \times 20.45\ \Omega\text{-m}$ (Assumption 1)

$\boldsymbol{E \leq 2.70\ V/m\ (0.82\ V/ft)}$ Threshold for high resistivity Case S

Table B2. Minimum electric field strengths (voltage gradients) sufficient to cause harmful physiological effects.

Water Resistivity (Ω-m)	Body Orientation*	Minimum Electric Field Strength (V/ft)	Minimum Electric Field Strength (V/in.)
2.16	A	0.54	0.05
11.34	A	1.41	0.12
11.34	S	0.74	0.06
26.32	S	0.82	0.07

* A denotes low water resistivity, electrical field is oriented in direction from chest to back. S denotes high water resistivity, body is oriented horizontally to the water's surface with the direction of the field oriented along the body's length.

Computations similar to those above were performed for two other zones of physiological effects DC-3 in Table B1 (strong involuntary muscular reactions) and DC-1 in Table B1 (slight prickling sensation). The results are summarized in Table B3. The lowest value where effects are likely, and therefore the worst case, was always Low Resistivity Case A. Note that in the strong involuntary muscular reactions zone there are two values for minimum electric field strengths. This is because the maximum body current is dependent on the pulse width. The minimum electric field strengths used in the determination of the ranges of physiological effects in the report are highlighted in bold text.

Table B3. Time-current zones for physiological effects of single-pulse DC shock for hand-to-ft pathway*.

Zones	Current Boundaries	2.5 ms Pulse Width**		4.0 ms Pulse Width**		6.5 ms Pulse Width**		Physiological Effects
		Maximum Body Current (mA)	Minimum Electric Field Strength (V/in.)	Maximum Body Current (mA)	Minimum Electric Field Strength (V/in.)	Maximum Body Current (mA)	Minimum Electric Field Strength (V/in.)	
DC-1	Up to 2.0 mA, Curve a	0.2	1.8E-4	0.2	1.8E-4	0.2	1.8E-4	Slight pricking sensation possible when making, breaking or rapidly altering current flow.
DC-2	2.0 mA up to Curve b	—	—	—	—	—	—	Involuntary muscular contractions likely, especially when making, breaking or rapidly altering current flow but usually no harmful electrical physiological effects.
DC-3	Curve b & above	34	0.03	29	0.03	24	0.02	Strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart may occur, increasing with current magnitude and time. Usually no organic damage to be expected.
DC-4	Above Curve c1	50	0.05	50	0.05	50	0.05	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, & burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time.
	Between Curves c1 & c2	—	—	—	—	—	—	DC-4.1: Probability of ventricular fibrillation increasing up to about 5%
	Between Curves c2 & c3	100	0.09	100	0.09	100	0.09	DC-4.2: Probability of ventricular fibrillation increasing up to about 50%
	Beyond Curve c3	138	0.12	138	0.12	138	0.12	DC-4.3: Probability of ventricular fibrillation above 50%

* Information in this table is reproduced from Table 13 of IEC Publication 60479-1.

** Since the minimum pulse width of FigureB1 (figure 22 of IEC 60479-1) is 10 ms, these maximum body current values were extrapolated from the curves.

Determination of range of harmful effects

Figures B2 and B3 show the threshold for ventricular fibrillation, ±0.05 V/in., overlaid on top of the electric fields measured over Barrier IIA, IIB, and I for run 1. These figures are representative as to how each run was analyzed to determine the range of harmful effects. The areas where the absolute peaks of the electric field are greater than ±0.05 V/in. are potentially dangerous for a person to be in the water. The center of Barrier II B was established as the X-axis zero point on Figure B2 for distance measurements north and south of Barriers IIA and B.

Isolated spikes in the voltage gradient beyond the main "humps" of voltage gradient created by the barriers are due to random electrical noise and are not considered harmful. Previous testing has shown that these spikes due to electrical noise are detected in the canal even when the barriers are not operating. (See [1, 3, and 4].)

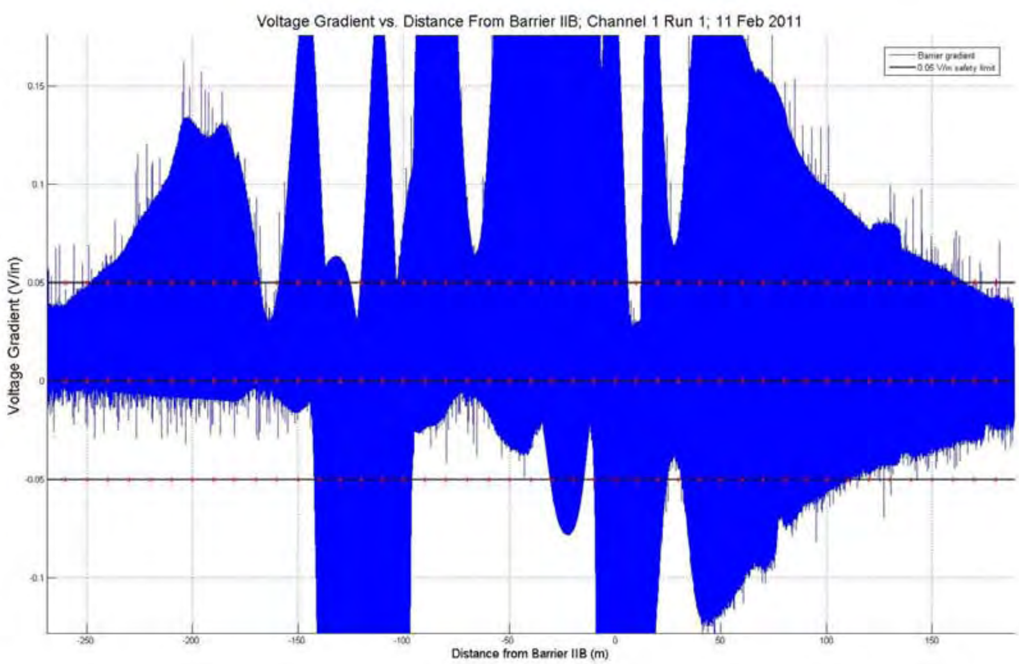

Figure B2. Example of minimum field strength shown on a plot of Barrier IIA and IIB field strength measurement run. Areas above or below the red lines are areas where the electric field strength from the barriers is sufficient to cause ventricular fibrillation (random isolated field spikes above these lines which occur outside the main area shown on the graph are noise and are not harmful).

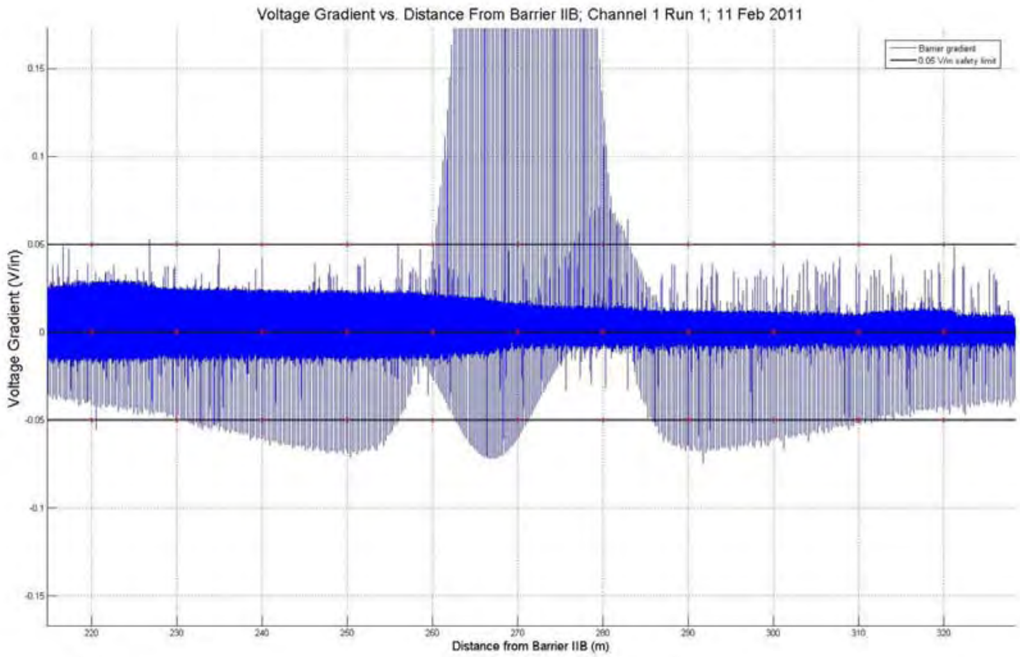

Figure B3. Example of minimum field strength shown on a plot of Barrier I field strength measurement run. Areas above or below the red lines are areas where the electric field strength from the barriers is sufficient to cause ventricular fibrillation (random isolated field spikes above these lines which occur outside the main area shown on the graph are noise and are not harmful).

Sensitivity analysis

Actual electric field strength sometimes exceeded the target operational pulser configuration specifications. In an effort to determine the impact of these higher values, a sensitivity analysis was conducted by scaling the entire dataset (i.e., run) by +/- 20% and then reevaluating the range of harmful effects using the scaled dataset. As an example of the effect of scaling, the scaled data for V12, Run1 on 11 February 2011 (Configuration Bravo), is shown in Figures B4 –B9.

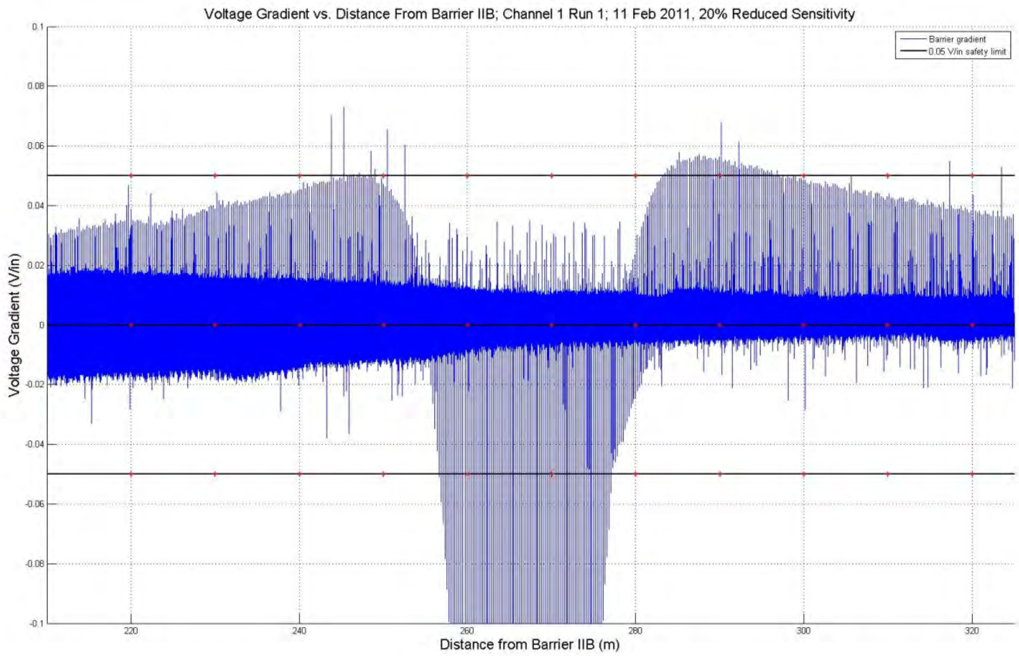

Figure B4. Sensitivity analysis at 20% reduced sensitivity 200 m away from Barrier IIB.

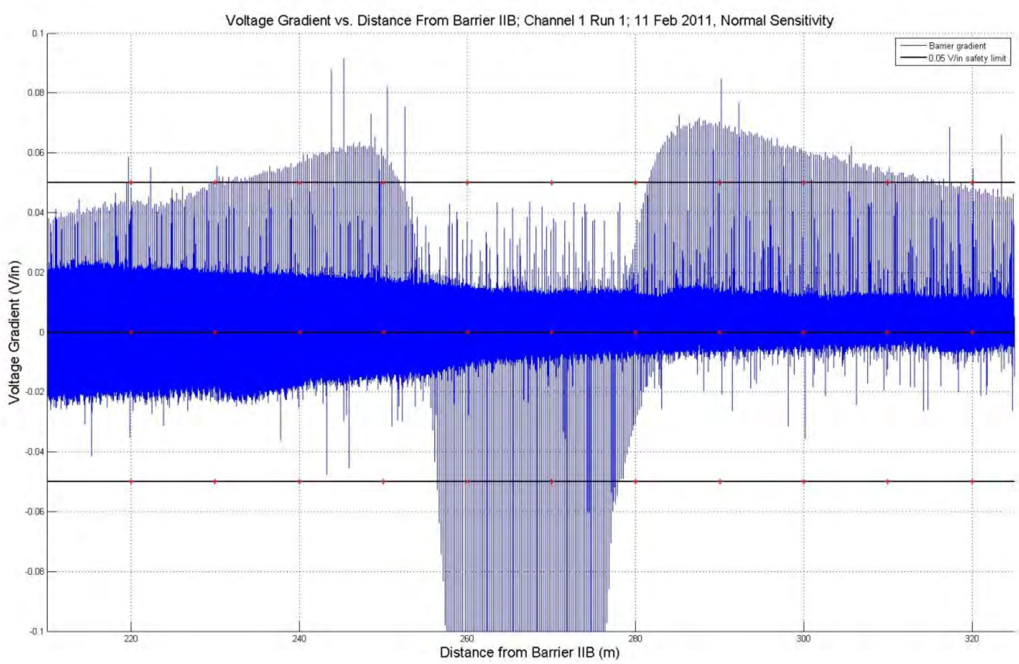

Figure B5. Sensitivity analysis at 20% normal sensitivity 200 m away from Barrier IIB.

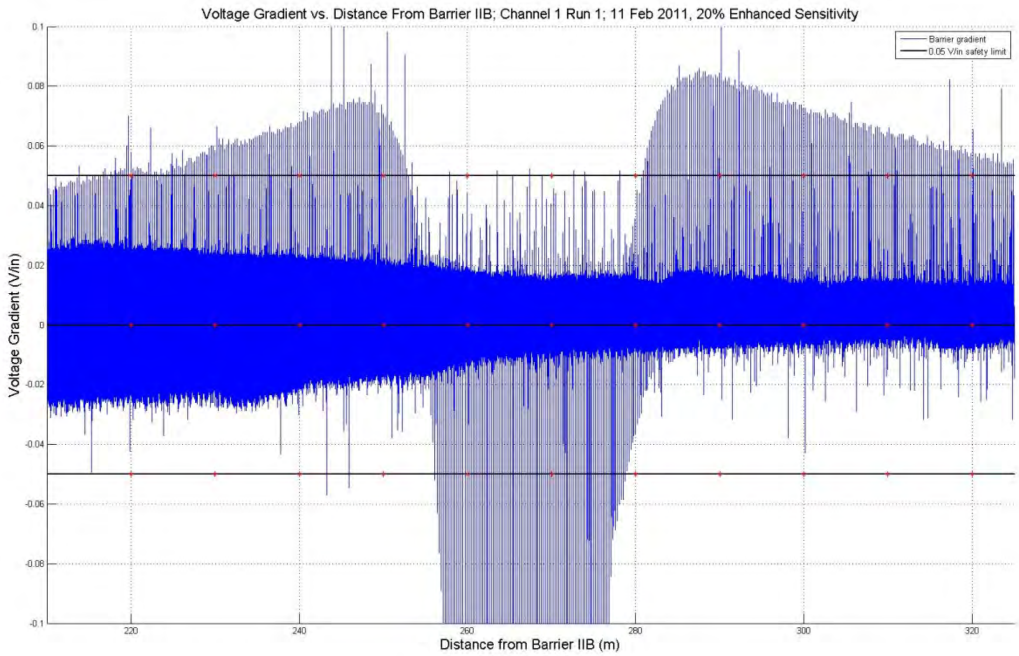

Figure B6. Sensitivity analysis at 20% enhanced sensitivity 200 m away from Barrier IIB.

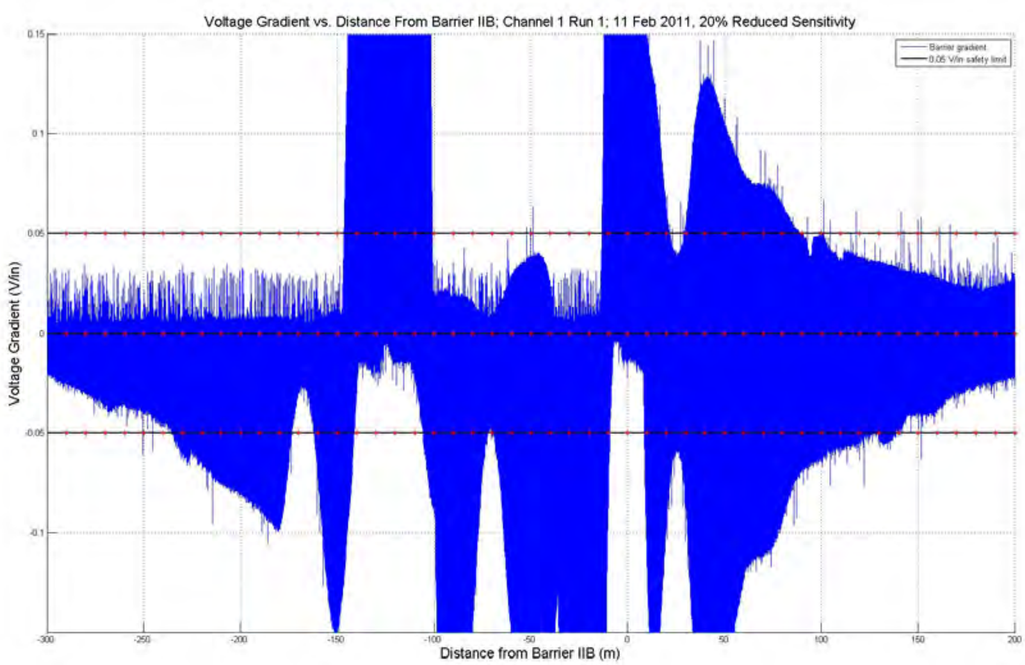

Figure B7. Sensitivity analysis at 20% reduced sensitivity at Barrier IIB.

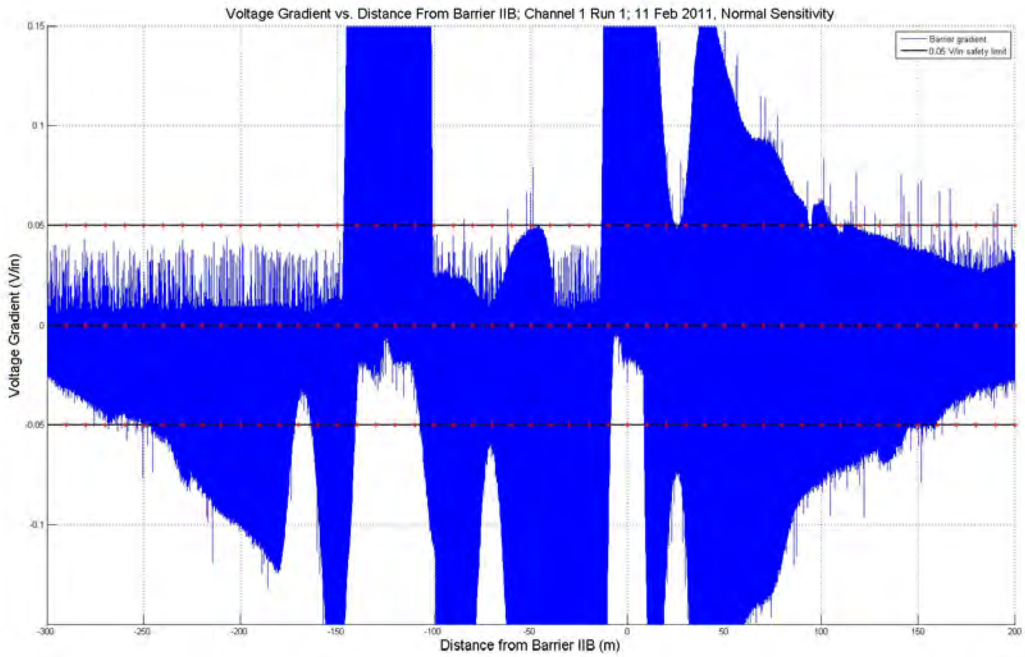

Figure B8. Sensitivity analysis at 20% normal sensitivity at Barrier IIB.

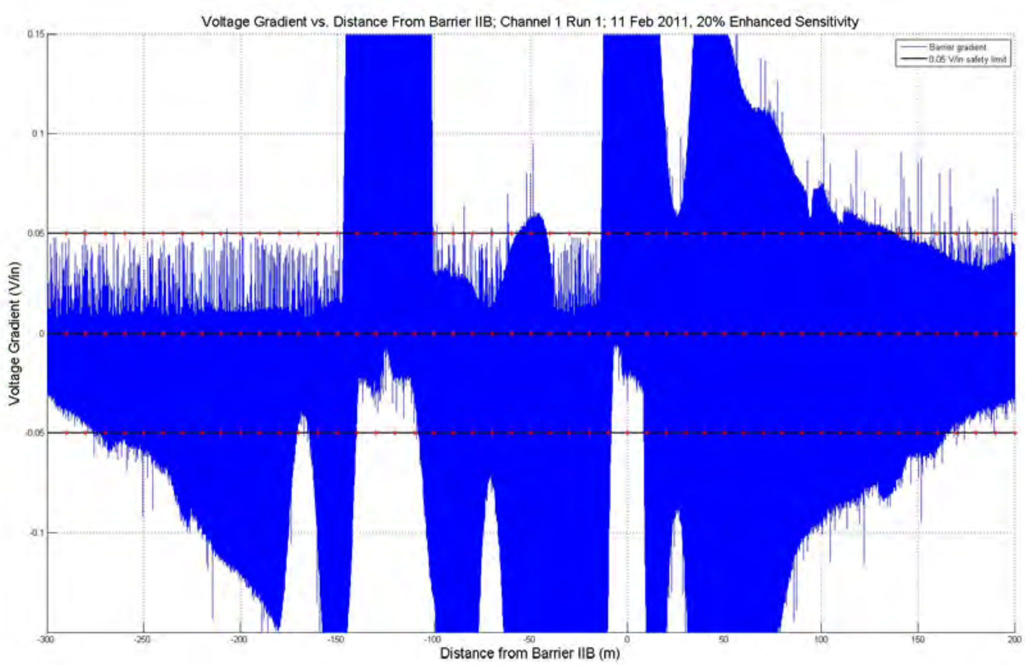

Figure B9. Sensitivity analysis at 20% enhanced sensitivity at Barrier IIB.

Appendix C: V12 Electric Field Plots

This appendix contains plots for V12 (channel 1) of the electric field mapping activity conducted on 11 and 12 February 2011 and 14 June 2011. In these plots, the electric field strength data has been georeferenced with respect to the center of the narrow array of Barrier IIB. This point is labeled measurement center on Figure C1. Figure 2 in the body of the report shows the location of measurement V12. Chapter 4, Table 2 in the body of the report provides details of the approximate run times as well as pulser and parasitic configurations for these data. Included on these plots is the electric field limit (0.05 V/in), above which is sufficient to cause harmful physiological effects.

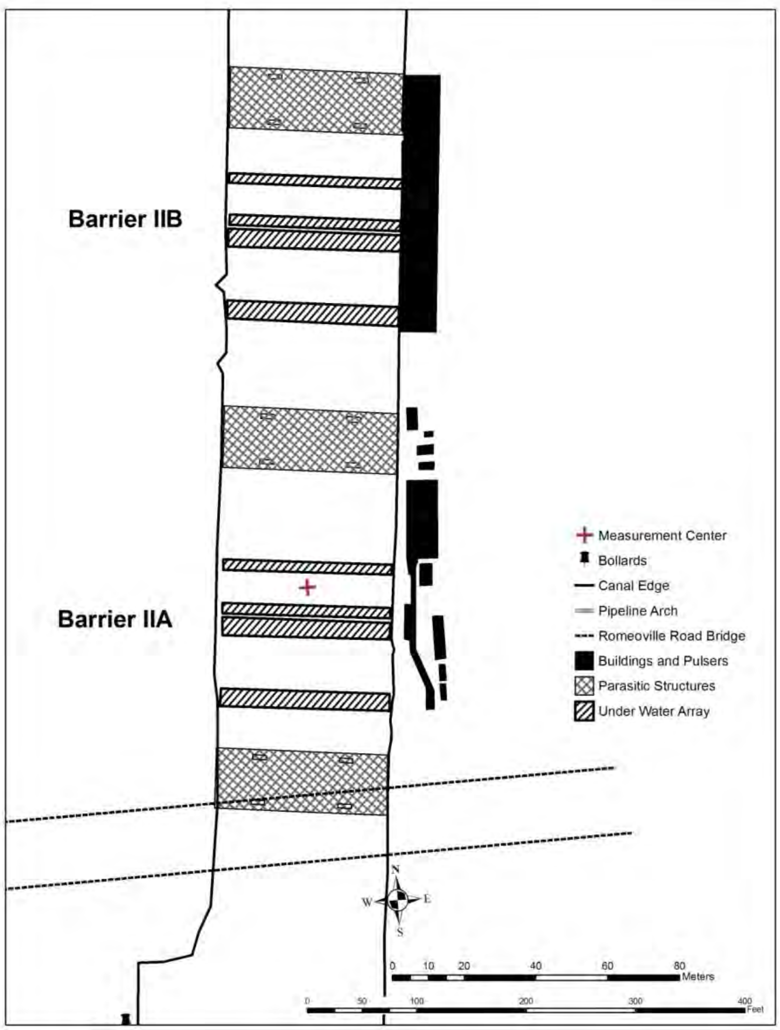

Figure C1. Location of reference point in canal for presentation of georeferenced data.

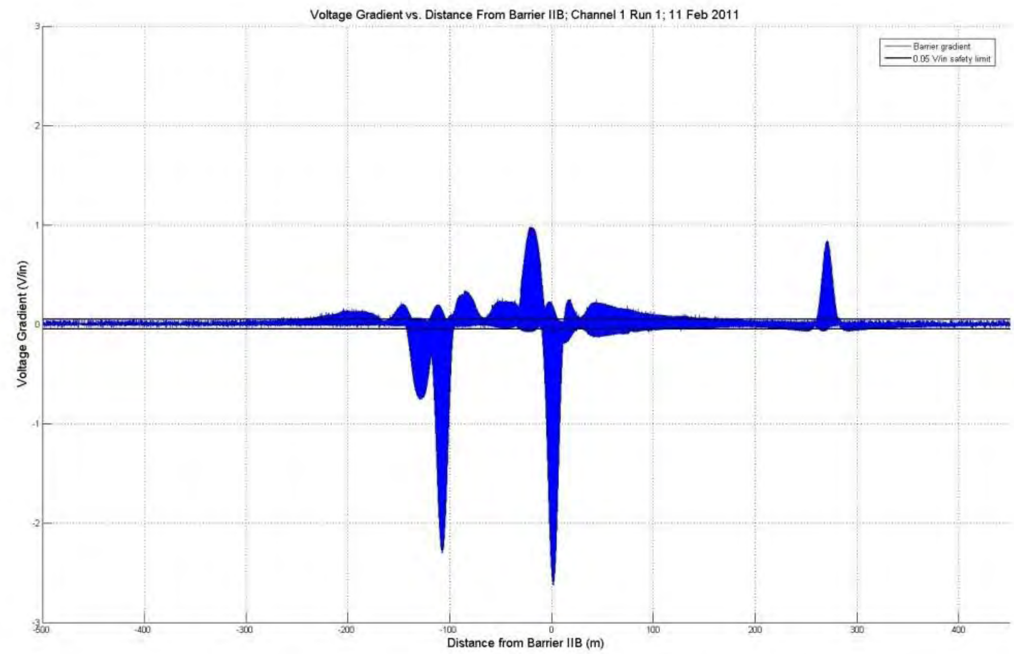

Figure C2. V12 for Run 1 on 11 February 2011 (Configuration B, Off, Off, Off, East Wall).

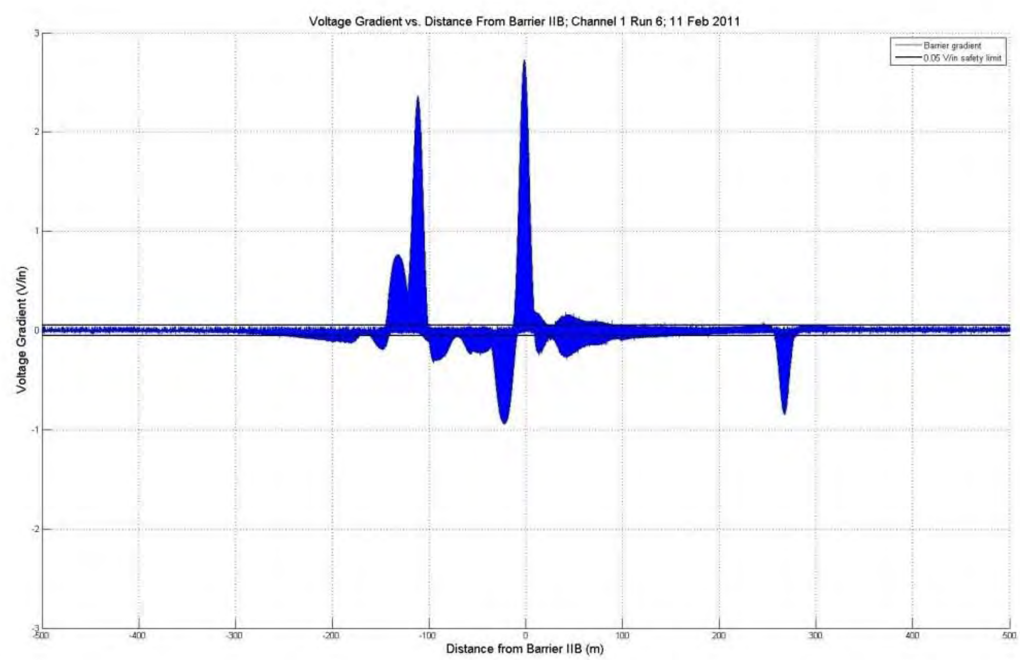

Figure C3. V12 for Run 6 on 11 February 2011 (Configuration B, Off, Off, Off, East Wall).

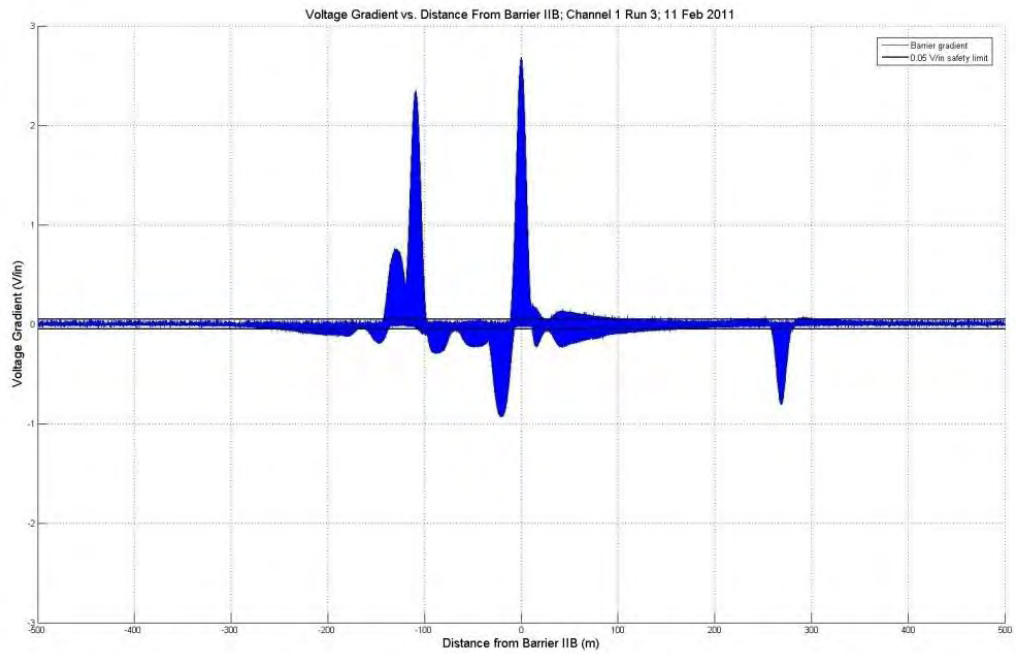

Figure C4. V12 for Run 3 on 11 February 2011 (Configuration B, Off, Off, Off, Center).

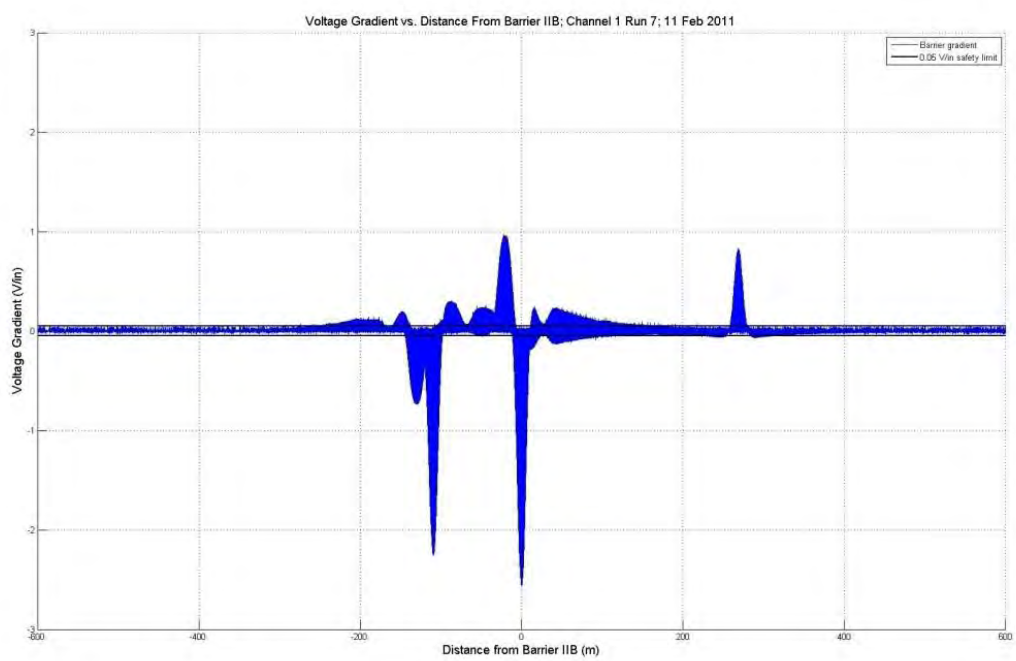

Figure C5. V12 for Run 7 on 11 February 2011 (Configuration B, Off, Off, Off, Center).

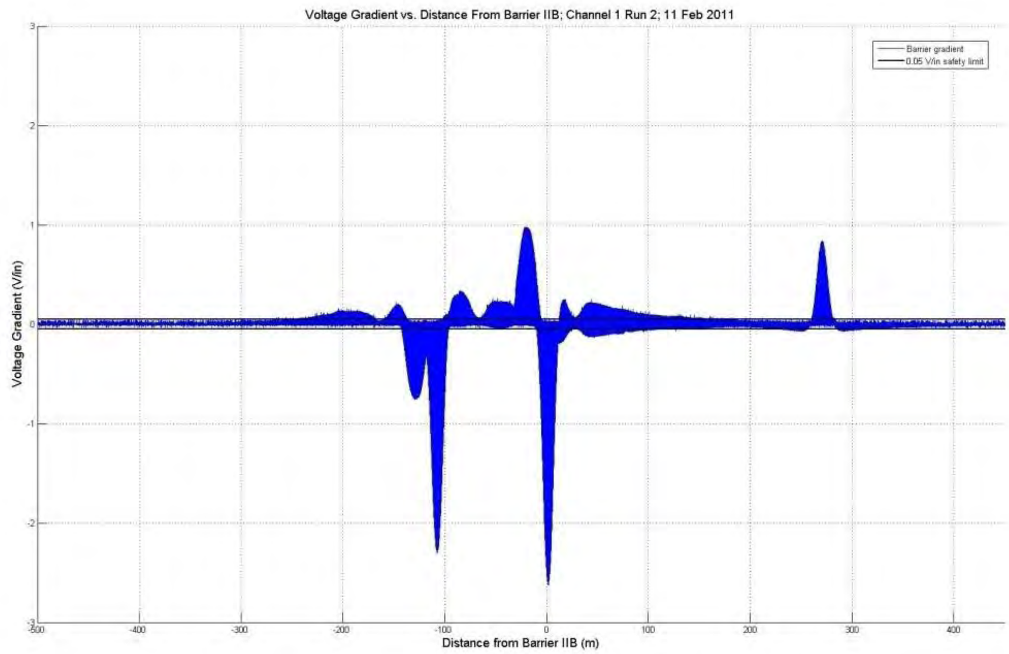

Figure C6. V12 for Run 2 on 11 February 2011 (Configuration B, Off, Off, Off, West Wall).

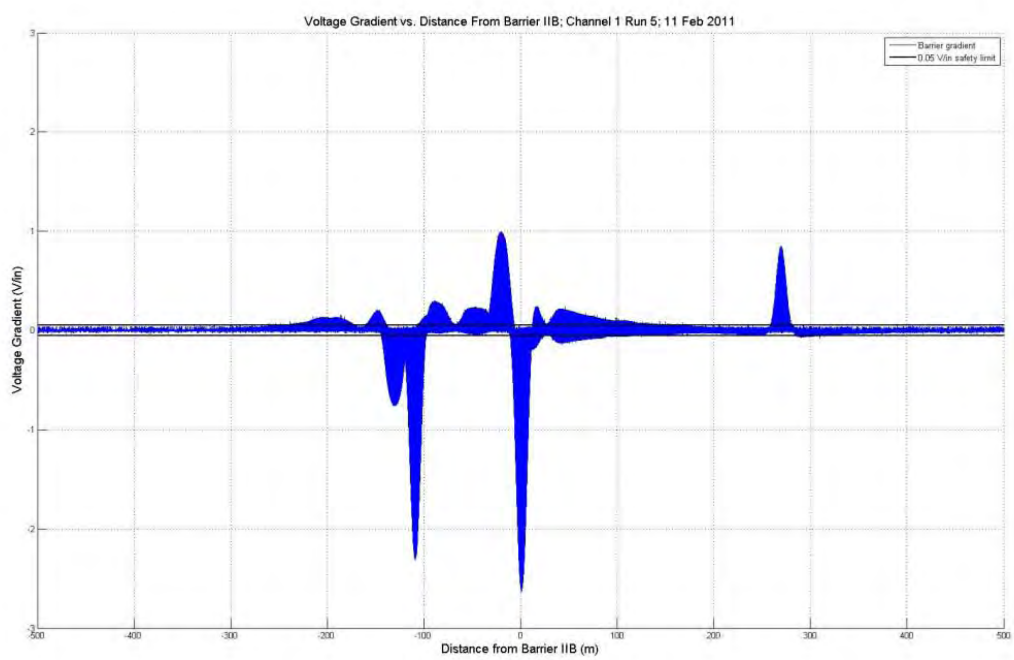

Figure C7. V12 for Run 5 on 11 February 2011 (Configuration B, Off, Off, Off, West Wall).

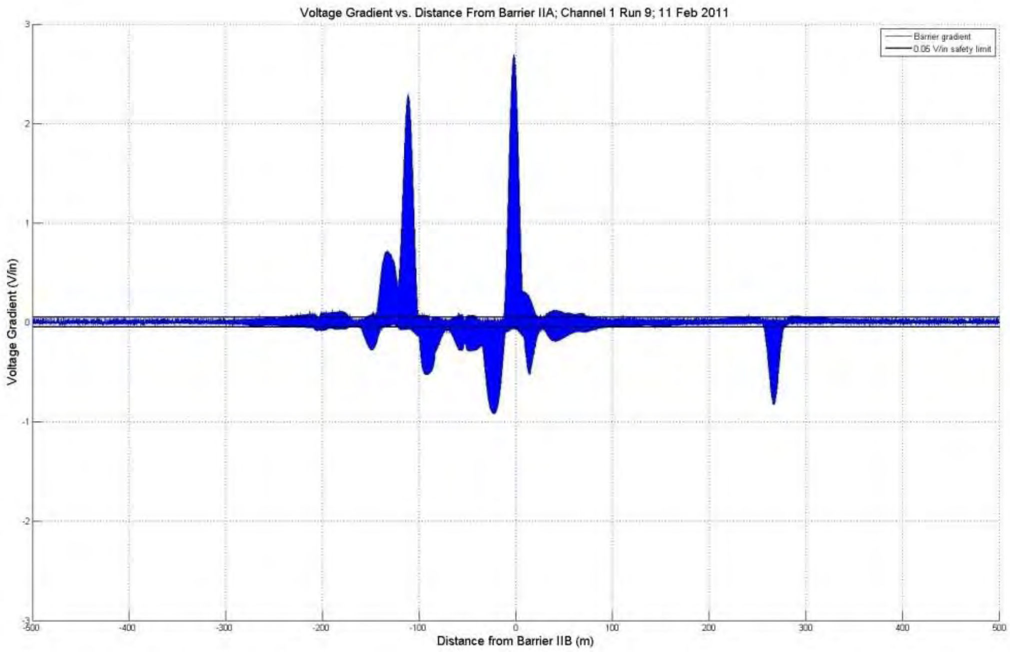

Figure C8. V12 for Run 9 on 11 February 2011 (Configuration B, On, Off, On, East Wall).

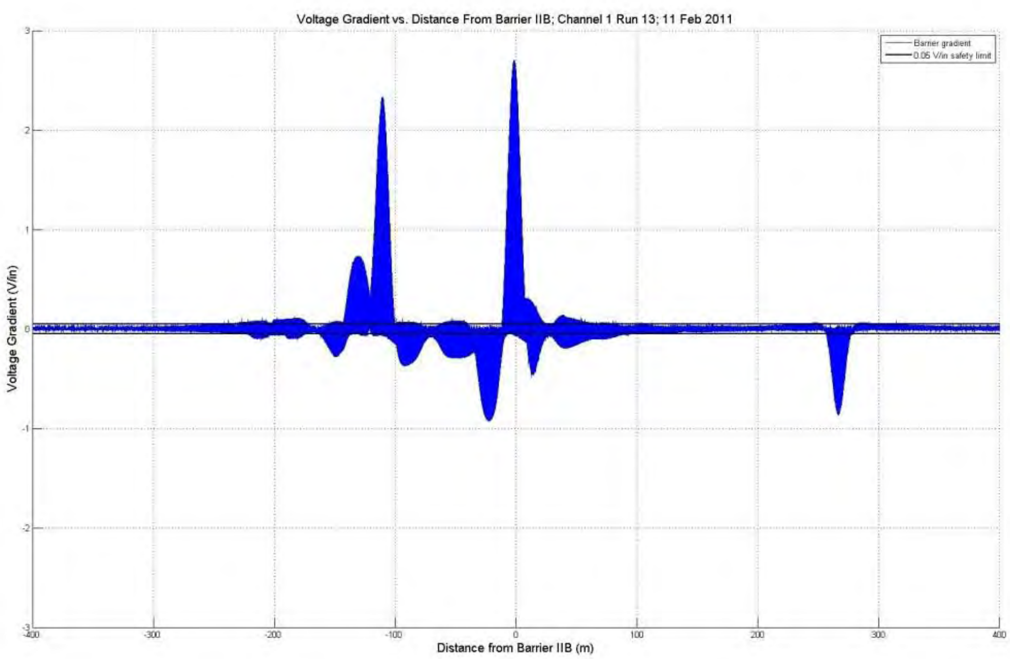

Figure C9. V12 for Run 13 on 11 February 2011 (Configuration B, On, Off, On, East Wall).

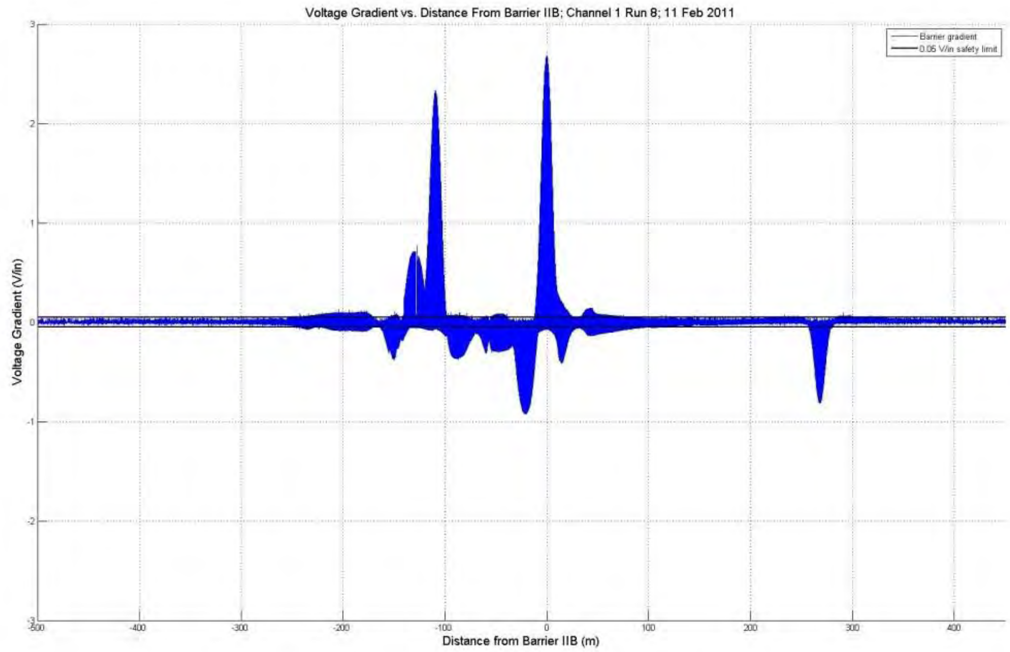

Figure C10. V12 for Run 8 on 11 February 2011 (Configuration B, On, Off, On, Center).

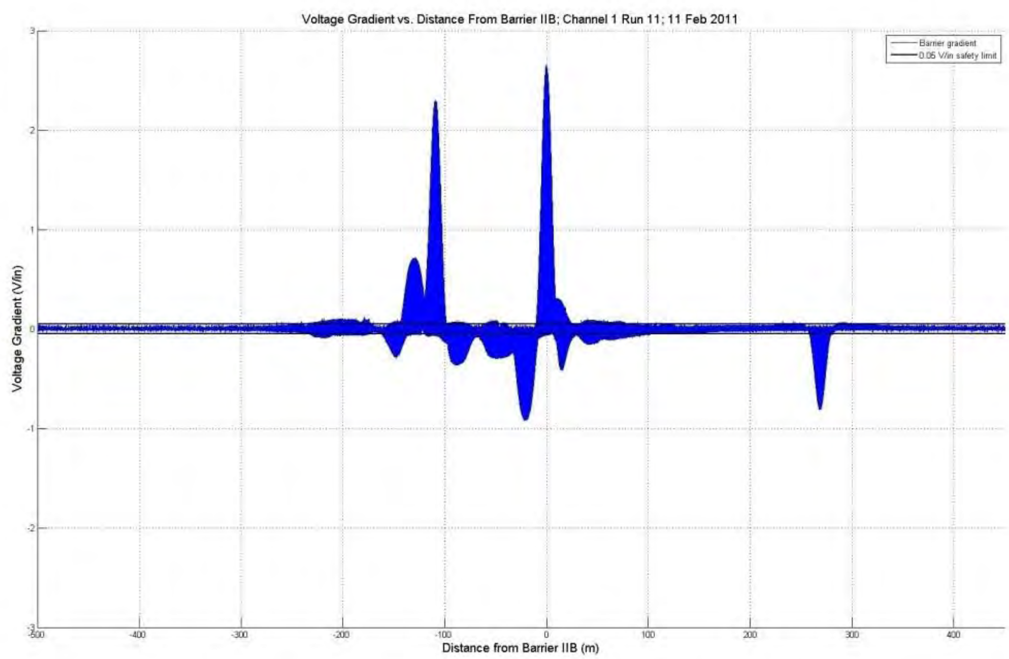

Figure C11. V12 for Run 11 on 11 February 2011 (Configuration B, On, Off, On, Center).

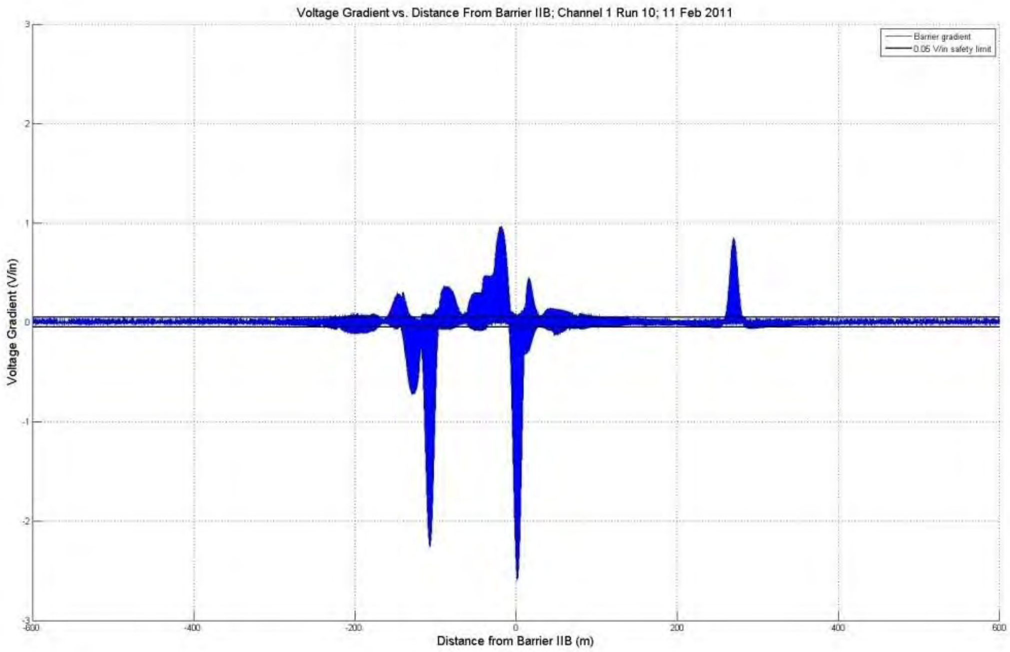

Figure C12. V12 for Run 10 on 11 February 2011 (Configuration B, On, Off, On, West Wall).

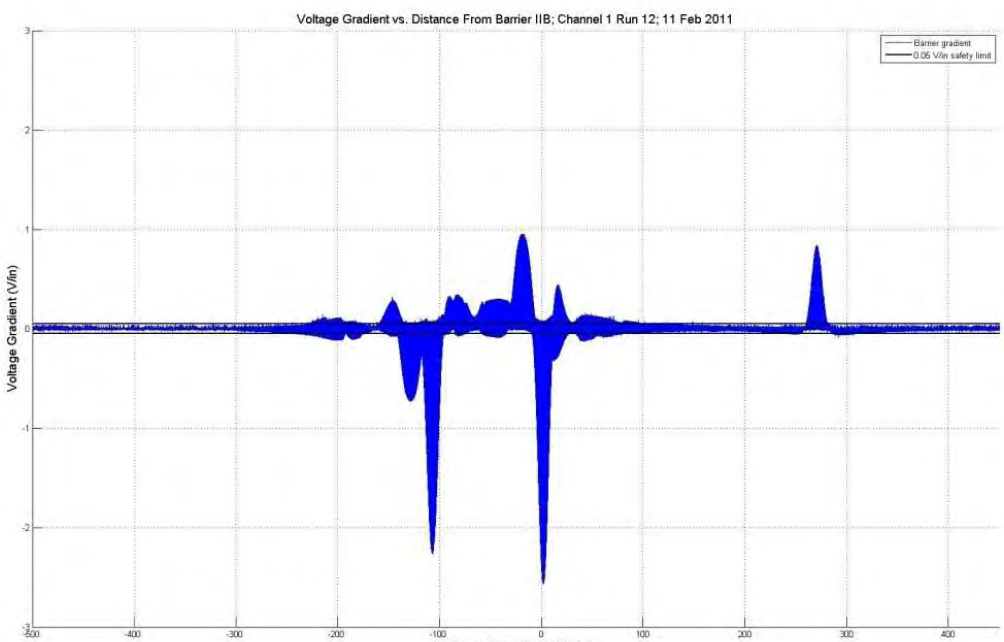

Figure C13. V12 for Run 12 on 11 February 2011 (Configuration B, On, Off, On, West Wall).

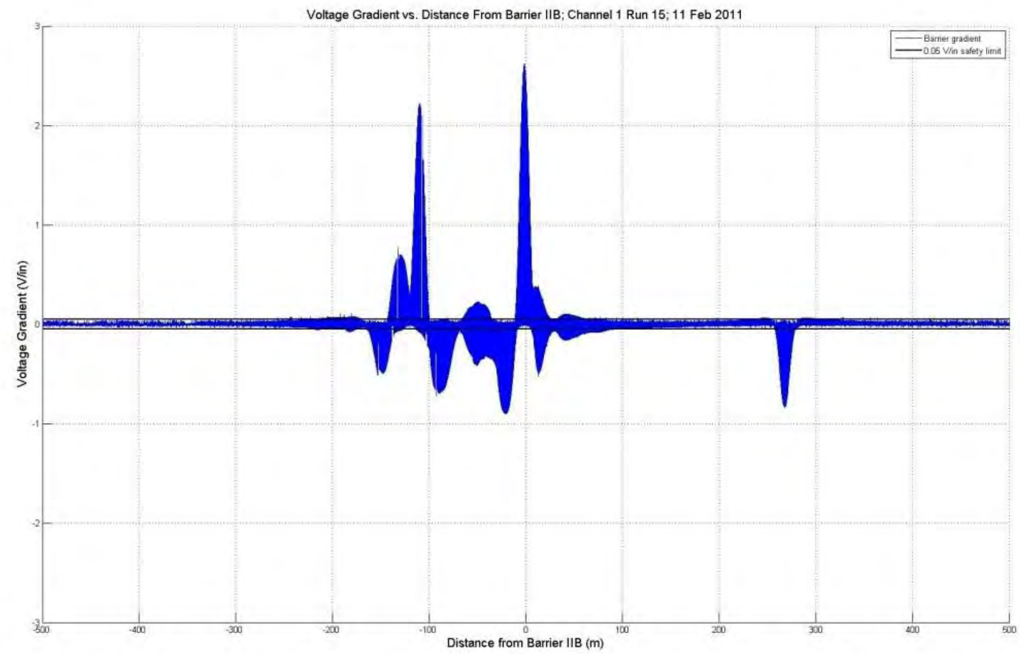

Figure C14. V12 for Run 15 on 11 February 2011 (Configuration B, On, On, On, East Wall).

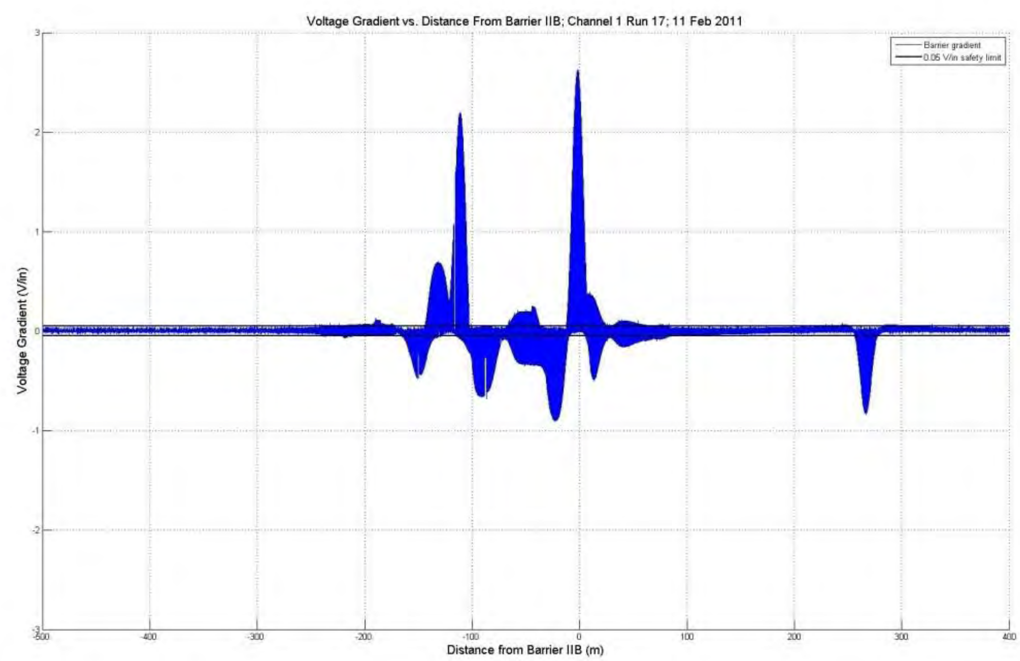

Figure C15. V12 for Run 17 on 11 February 2011 (Configuration B, On, On, On, East Wall).

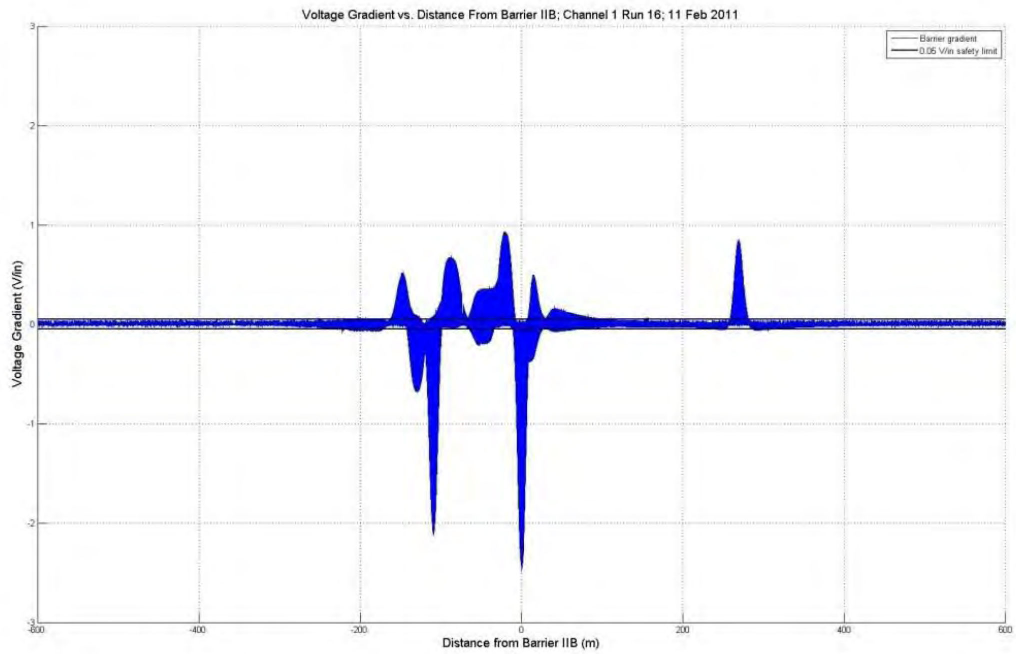

Figure C16. V12 for Run 16 on 11 February 2011 (Configuration B, On, On, On, Center).

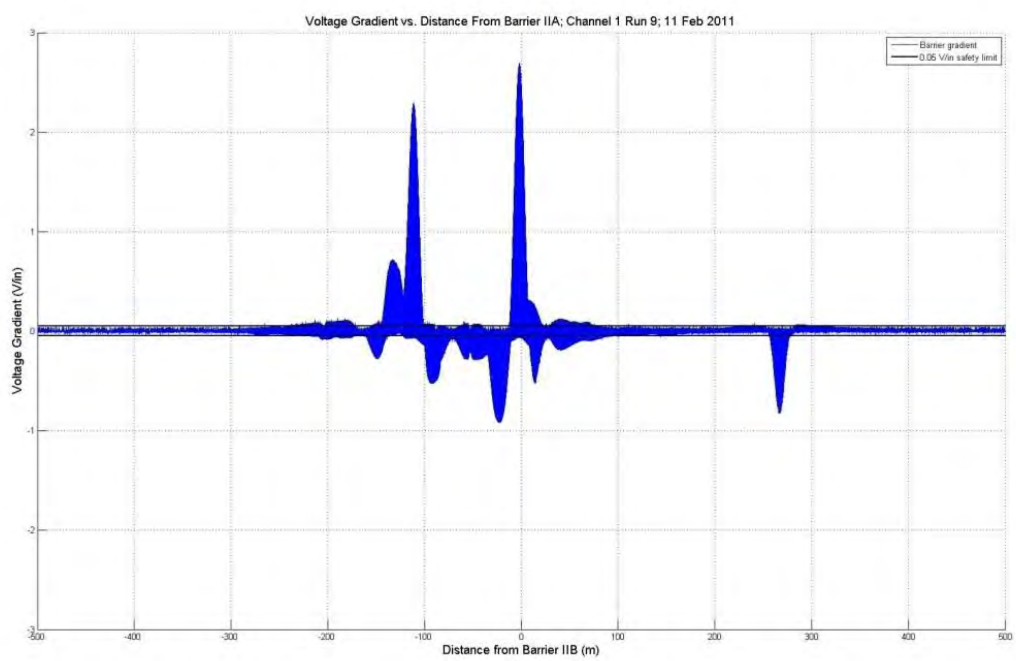

Figure C17. V12 for Run 19 on 11 February 2011 (Configuration B, On, On, On, Center).

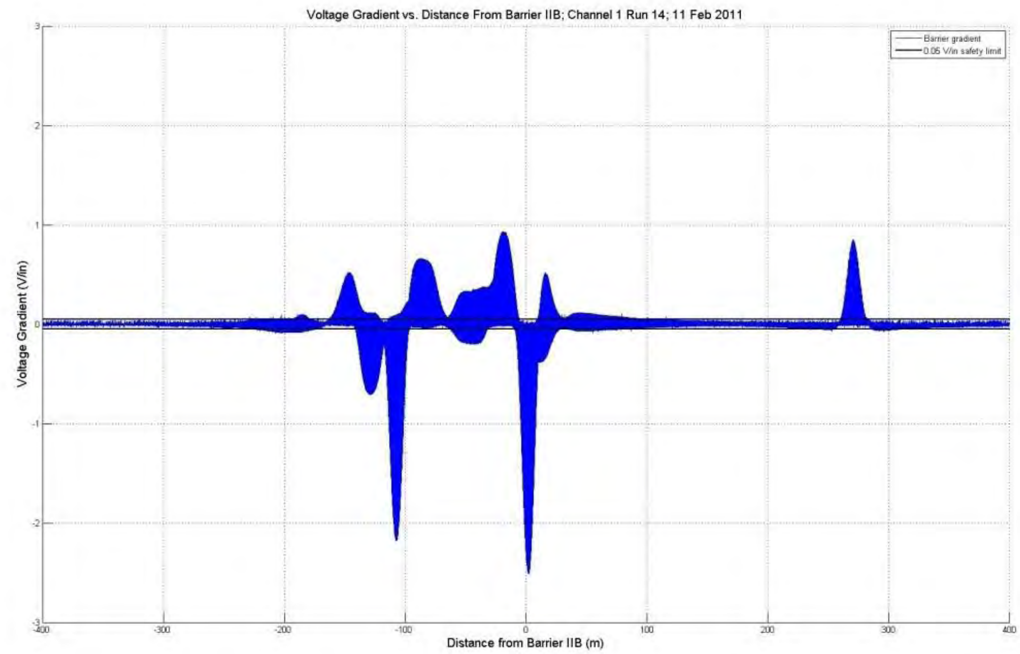

Figure C18. V12 for Run 14 on 11 February 2011 (Configuration B, On, On, On, West Wall).

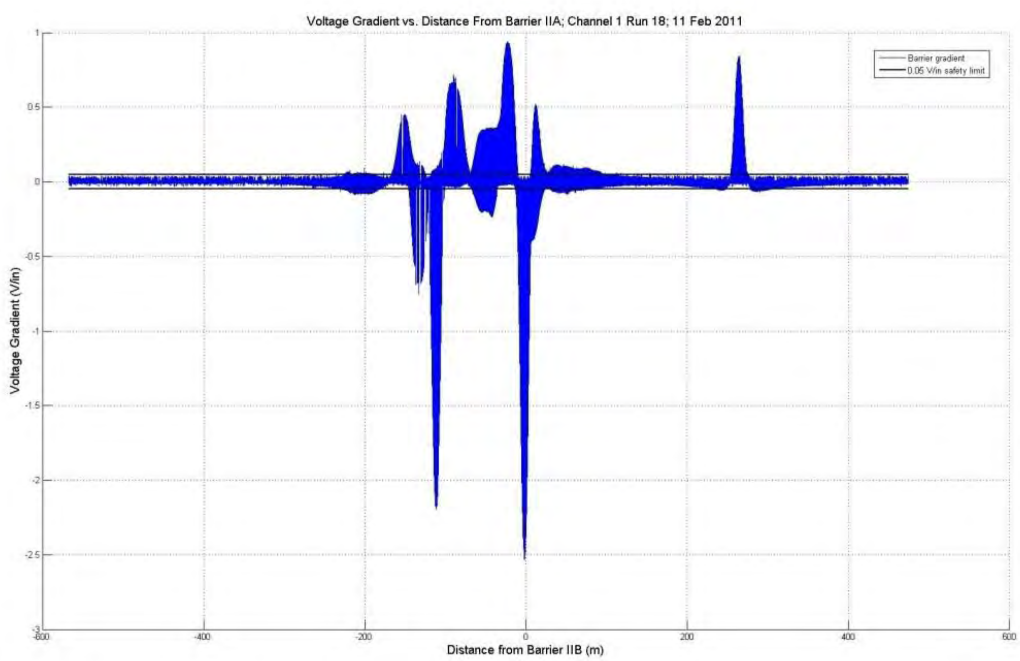

Figure C19. V12 for Run 18 on 11 February 2011 (Configuration B, On, On, On, West Wall).

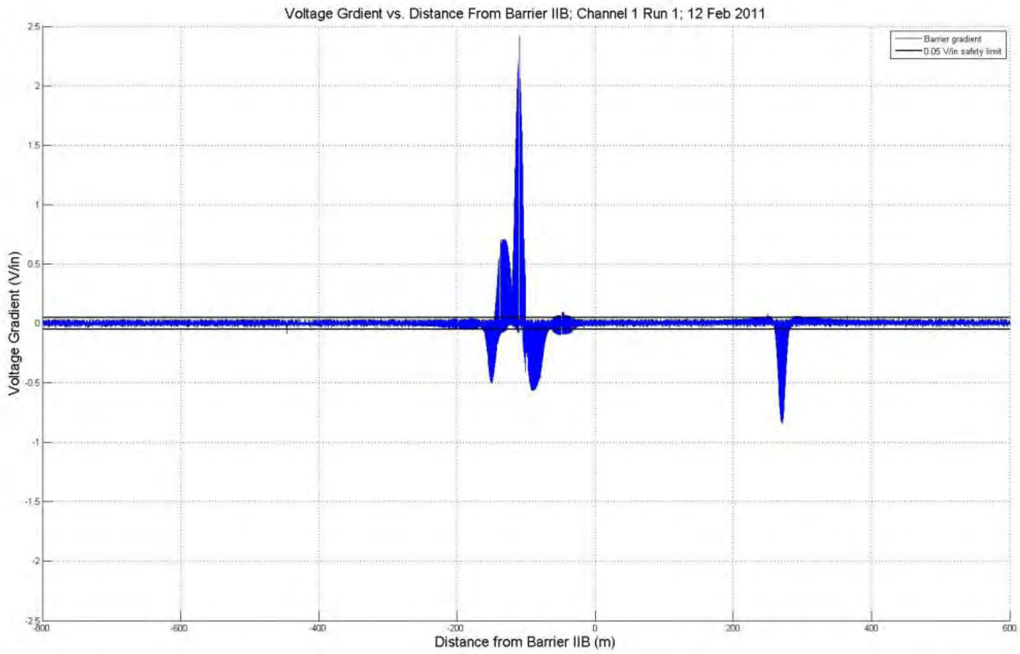

Figure C20. V12 for Run 1 on 12 February 2011. (Configuration D, On, On, Off, East Wall).

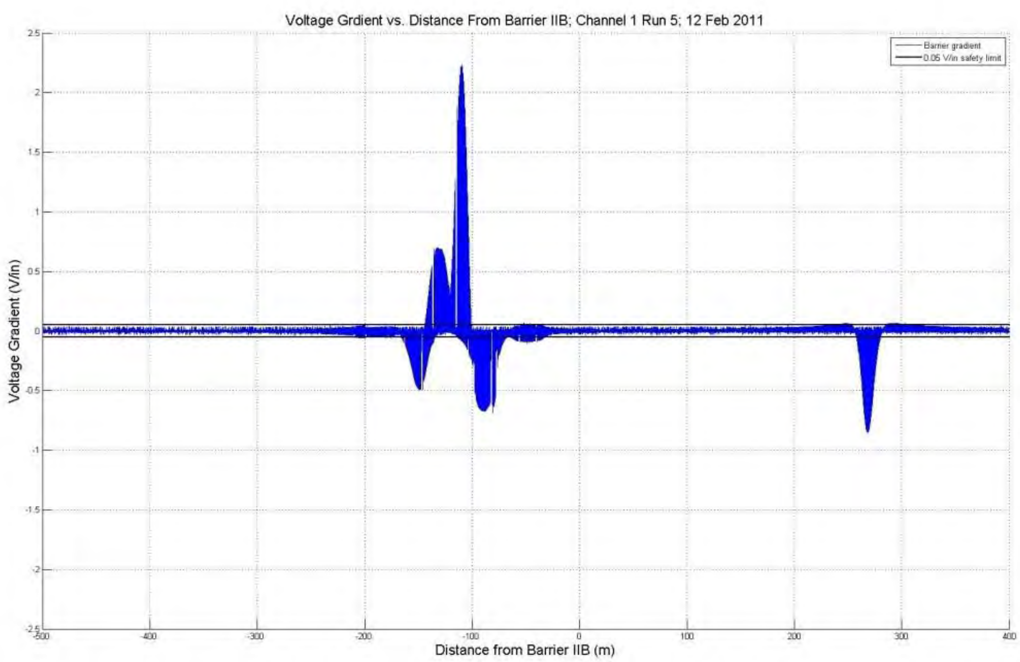

Figure C21. V12 for Run 5 on 12 February 2011 (Configuration D, On, On, Off, East Wall).

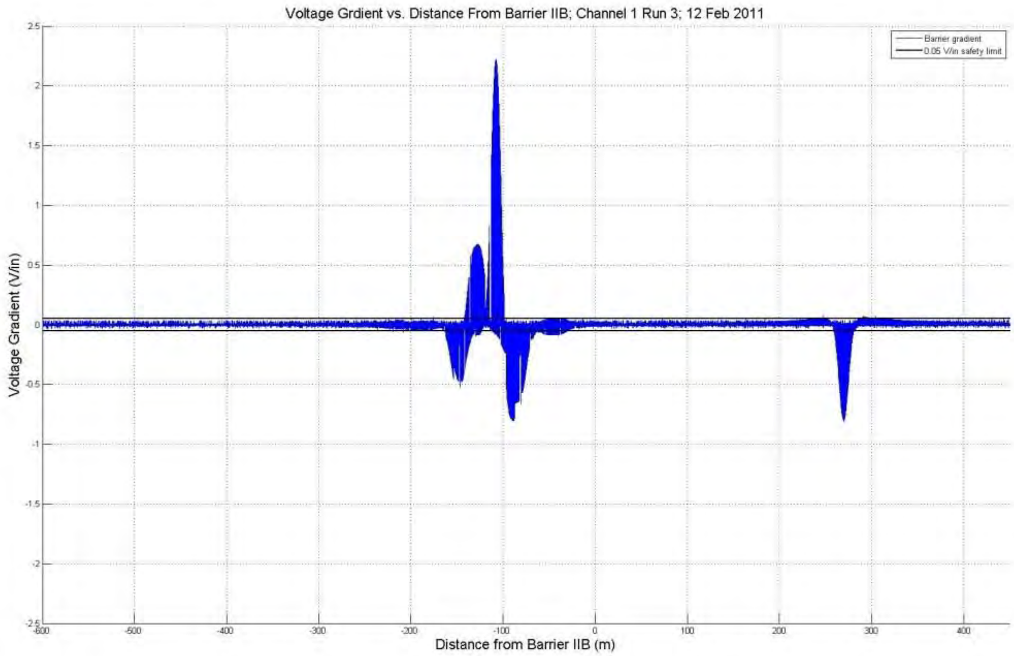

Figure C22. V12 for Run 3 on 12 February 2011 (Configuration D, On, On, Off, Center).

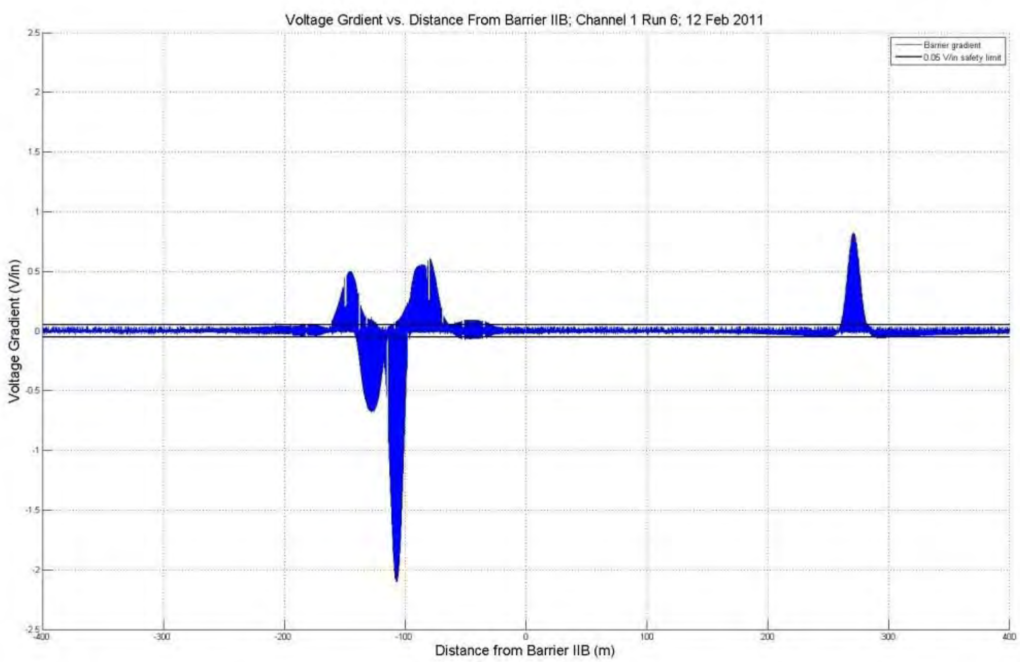

Figure C23. V12 for Run 6 on 12 February 2011 (Configuration D, On, On, Off, Center).

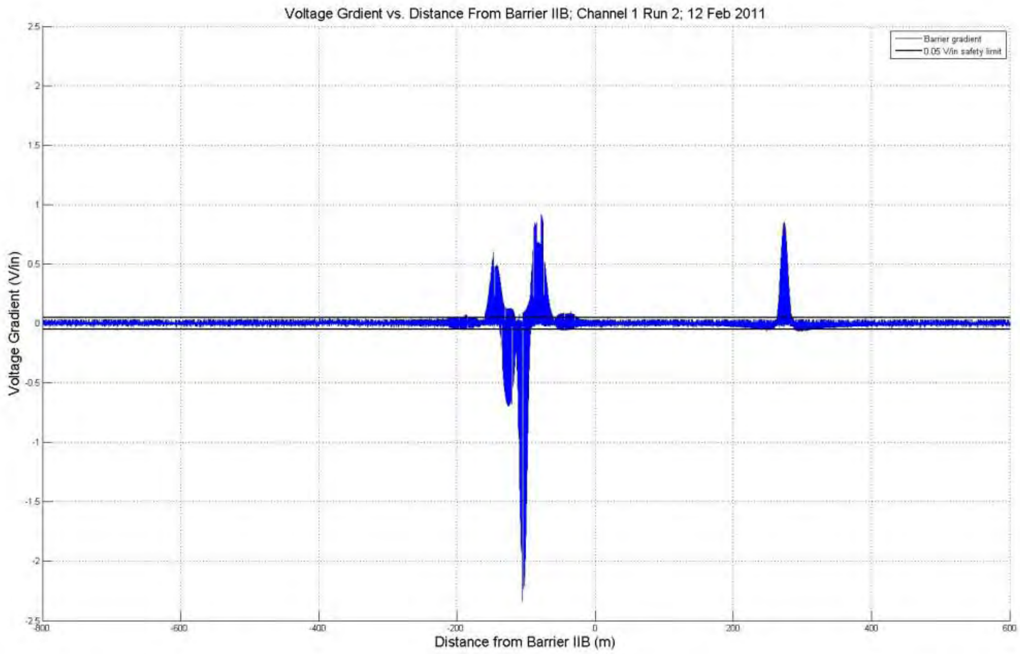

Figure C24. V12 for Run 2 on 12 February 2011 (Configuration D, On, On, Off, West Wall).

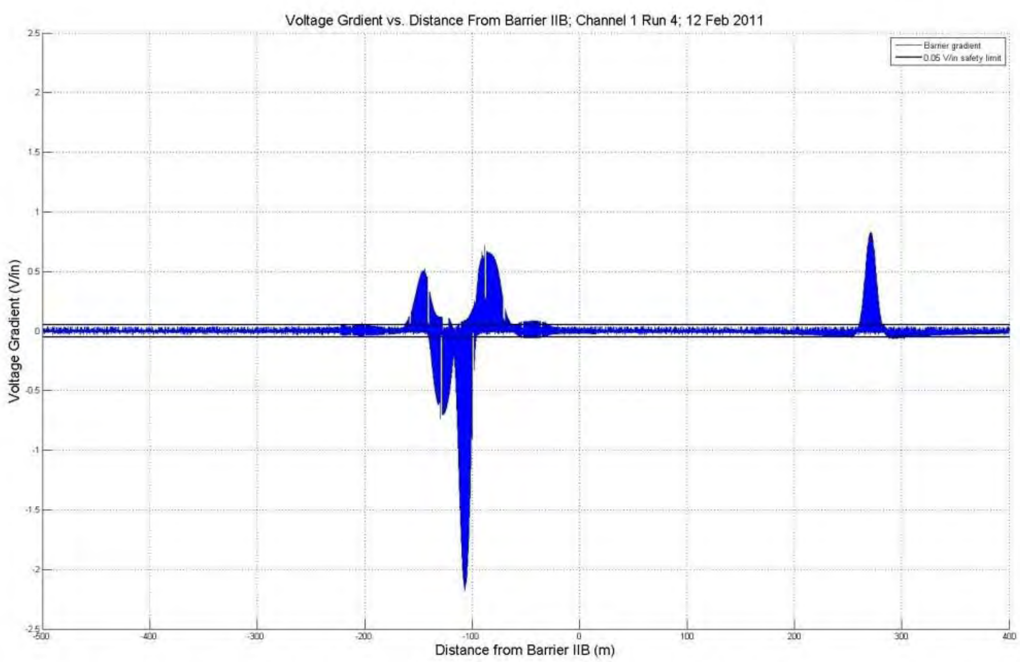

Figure C25. V12 for Run 4 on 11 February 2011 (Configuration D, On, On, Off, West Wall).

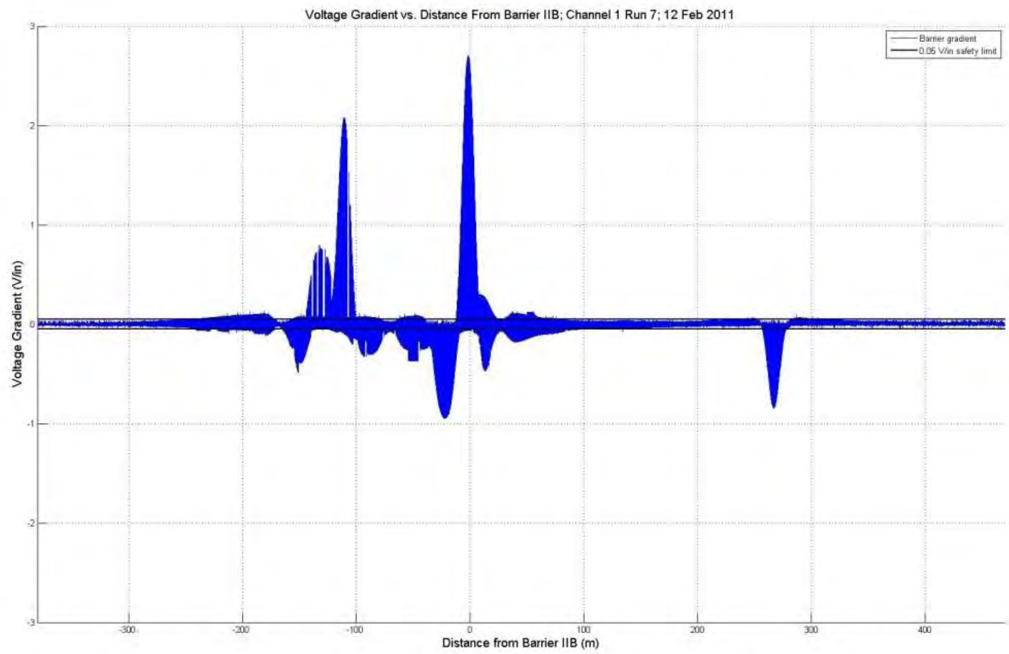

Figure C26. V12 for Run 7 on 12 February 2011 (Configuration A, On, Off, On, East Wall).

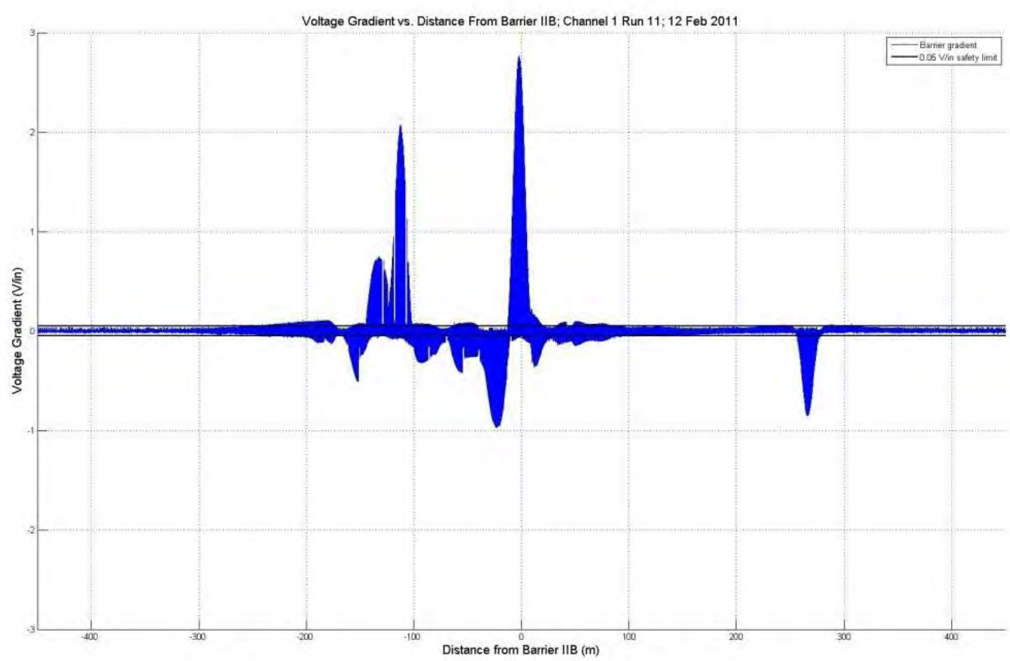

Figure C27. V12 for Run 11 on 12 February 2011 (Configuration A, On, Off, On, East Wall).

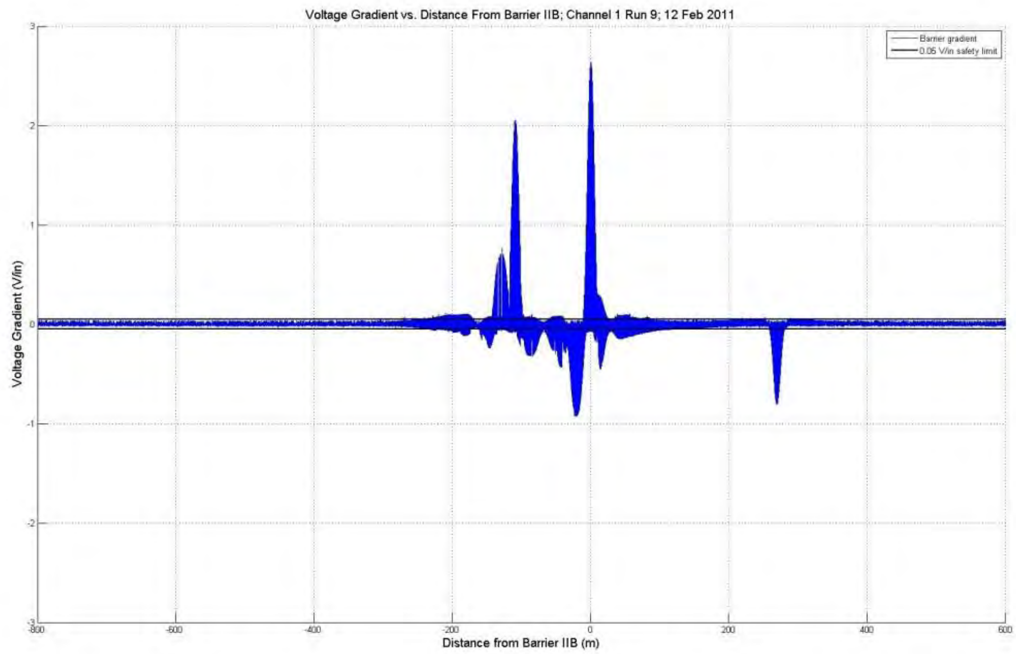

Figure C28. V12 for Run 9 on 12 February 2011 (Configuration A, On, Off, On, Center).

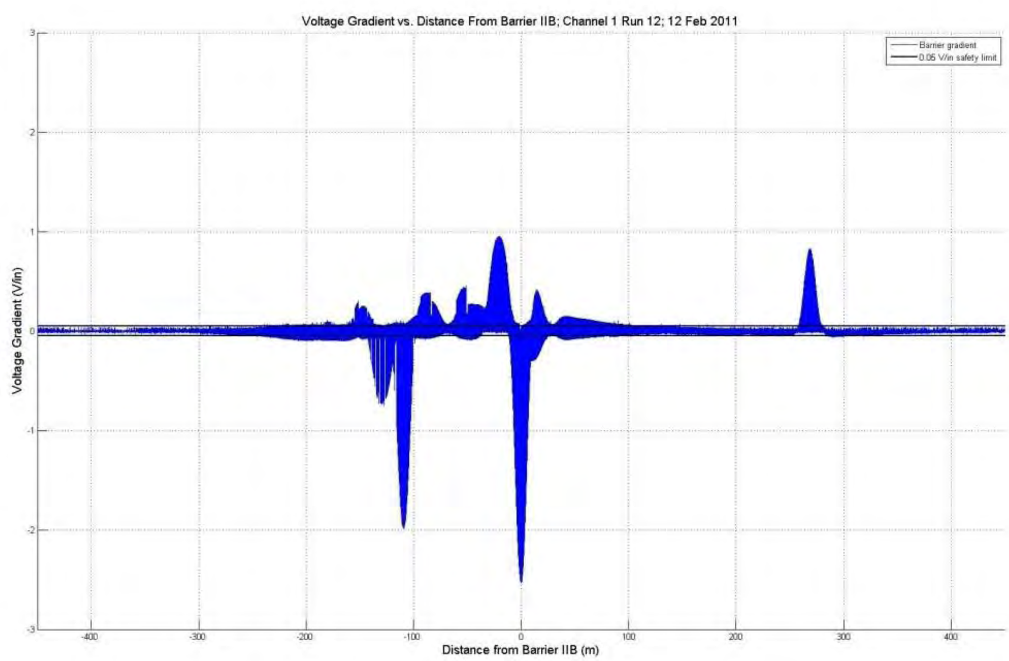

Figure C29. V12 for Run 12 on 12 February 2011 (Configuration A, On, Off, On, Center Wall).

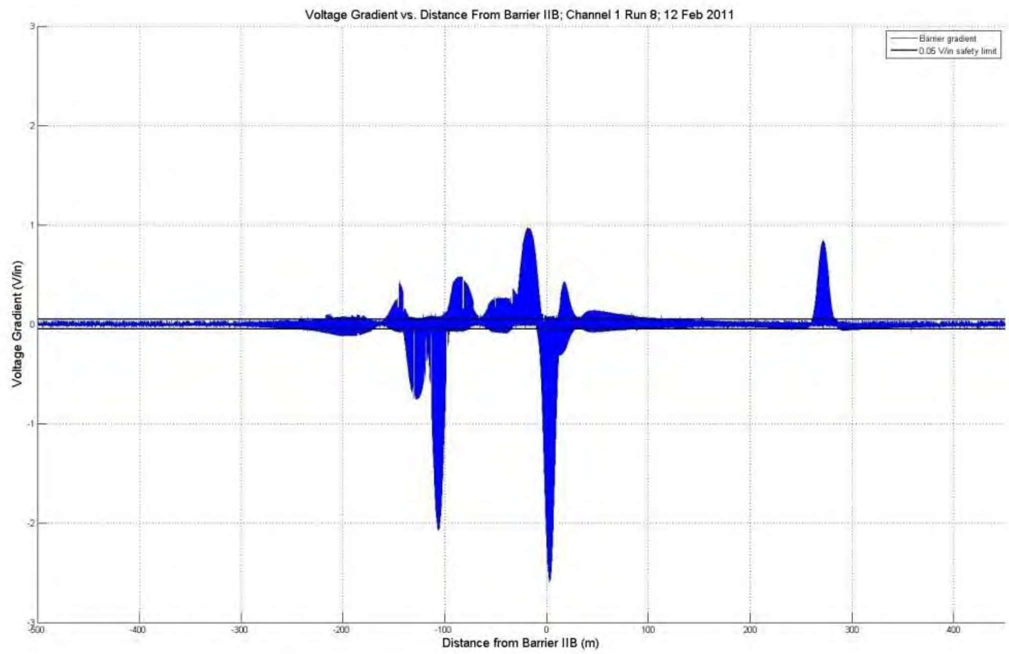

Figure C30. V12 for Run 8 on 12 February 2011 (Configuration A, On, Off, On, West Wall).

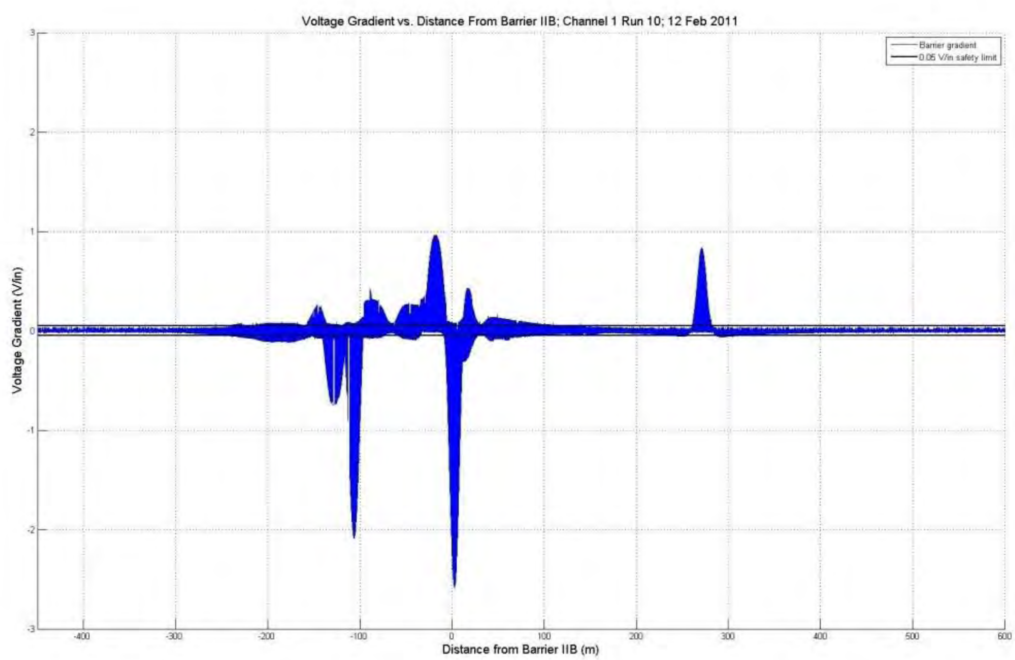

Figure C31. V12 for Run 10 on 12 February 2011 (Configuration A, On, Off, On, West Wall).

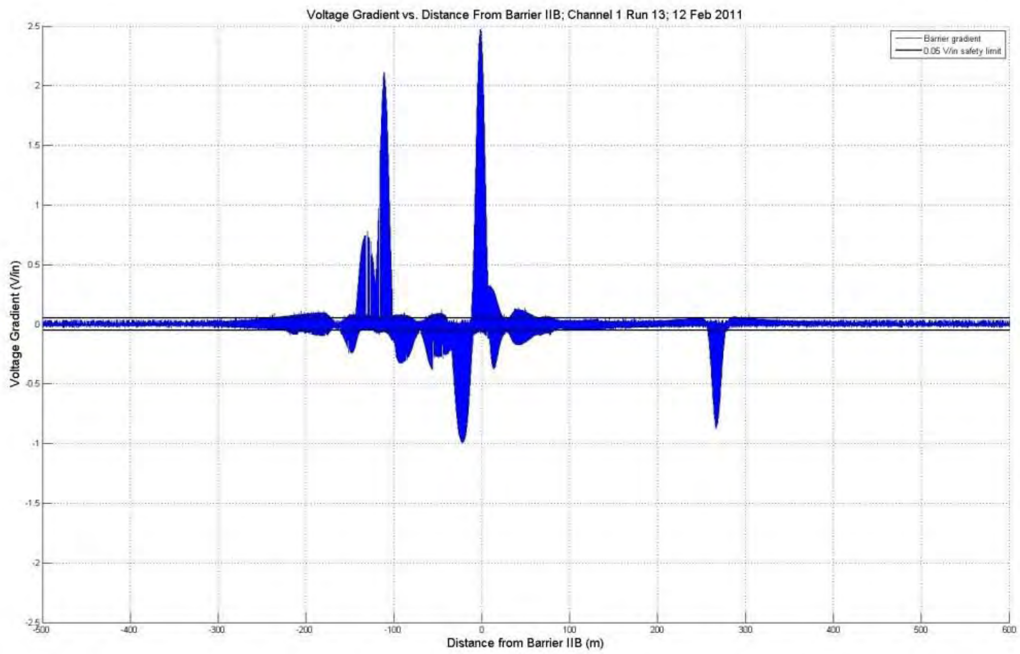

Figure C32. V12 for Run 13 on 12 February 2011 (Configuration C, On, Off, On, East Wall).

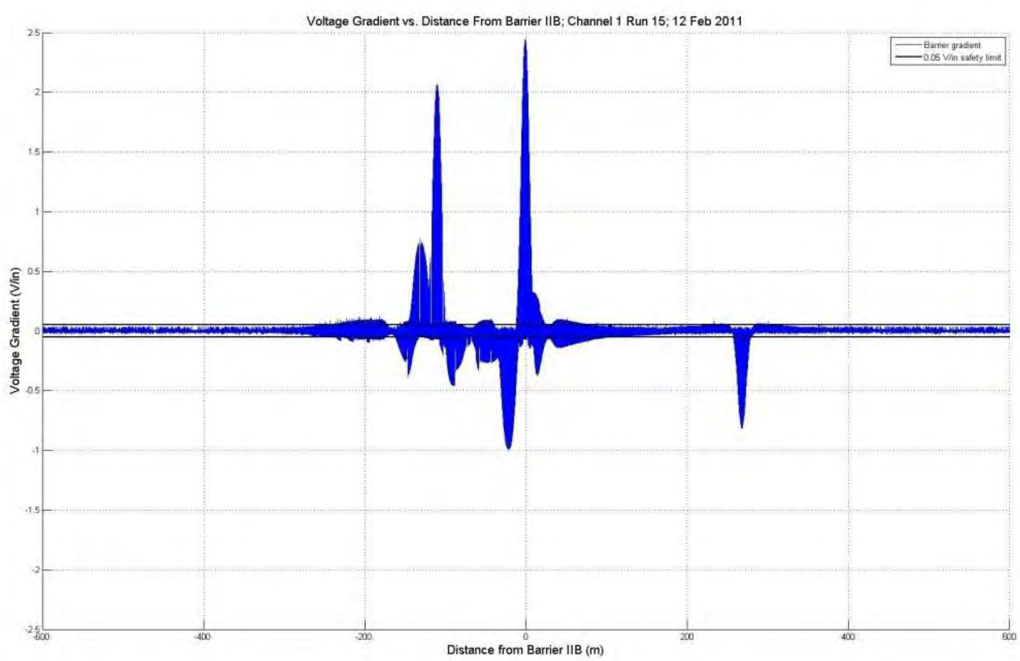

Figure C33. V12 for Run 15 on 12 February 2011 (Configuration C, On, Off, On, Center Wall).

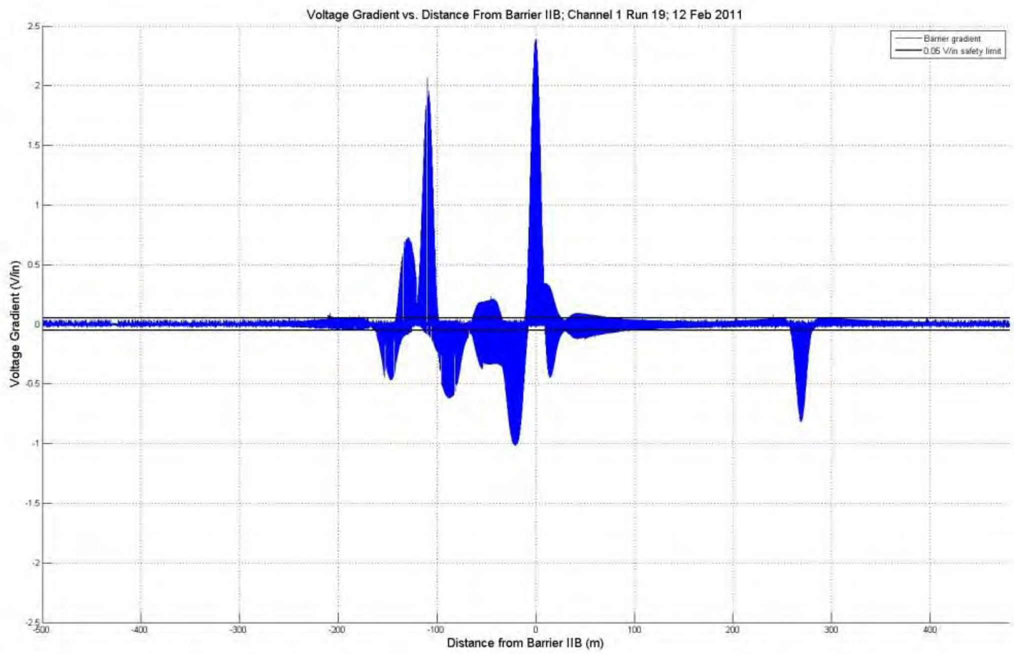

Figure C34. V12 for Run 19 on 12 February 2011 (Configuration C, On, Off, On, Center Wall).

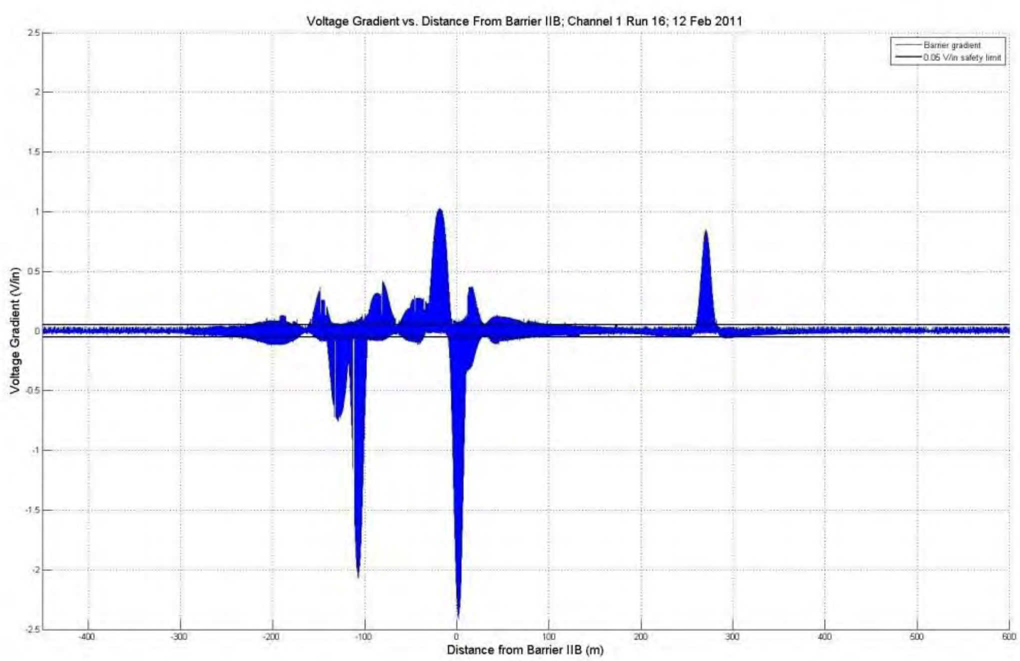

Figure C35. V12 for Run 16 on 12 February 2011 (Configuration C, On, Off, On, West Wall).

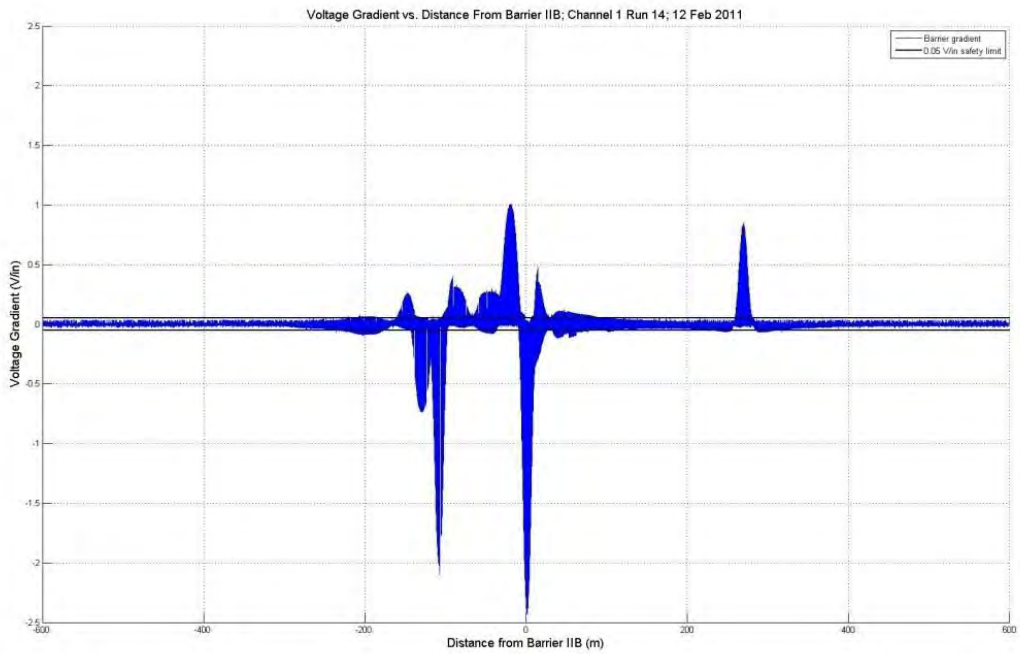

Figure C36. V12 for Run 14 on 12 February 2011 (Configuration C, On, Off, On, West Wall).

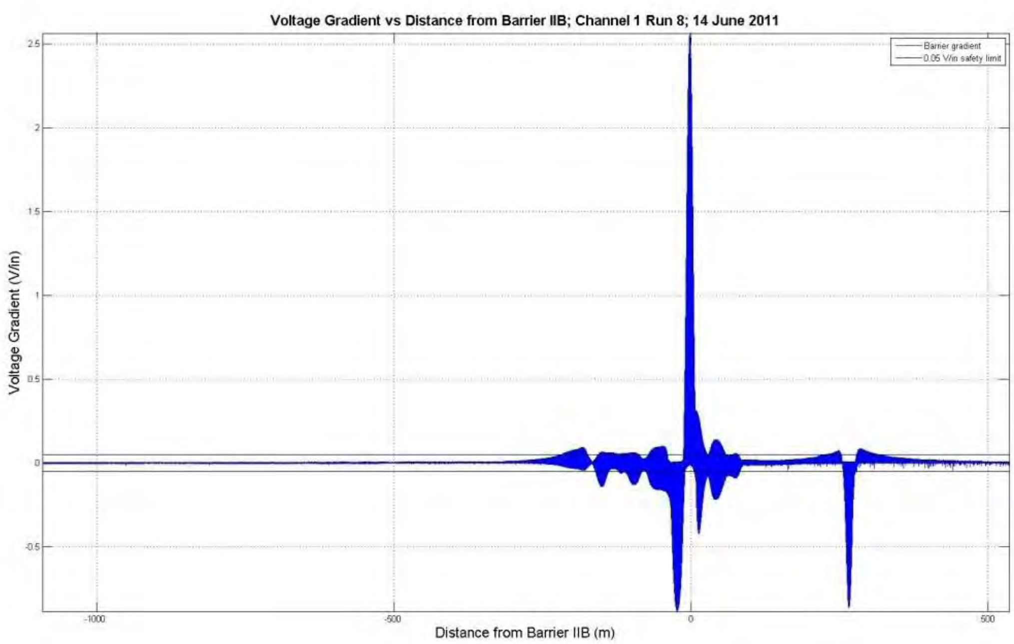

Figure C37. V12 for Run 8 on 14 June 2011 (Configuration E, On Off, On, East Wall).

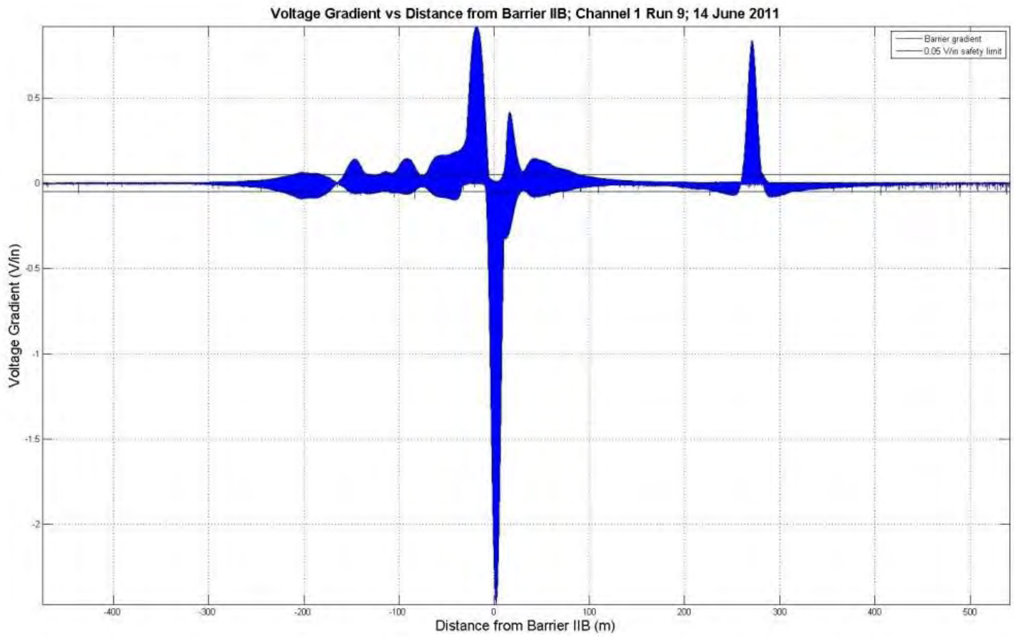

Figure C38. V12 for Run 9 on 14 June 2011 (Configuration E, On Off, On, East Wall).

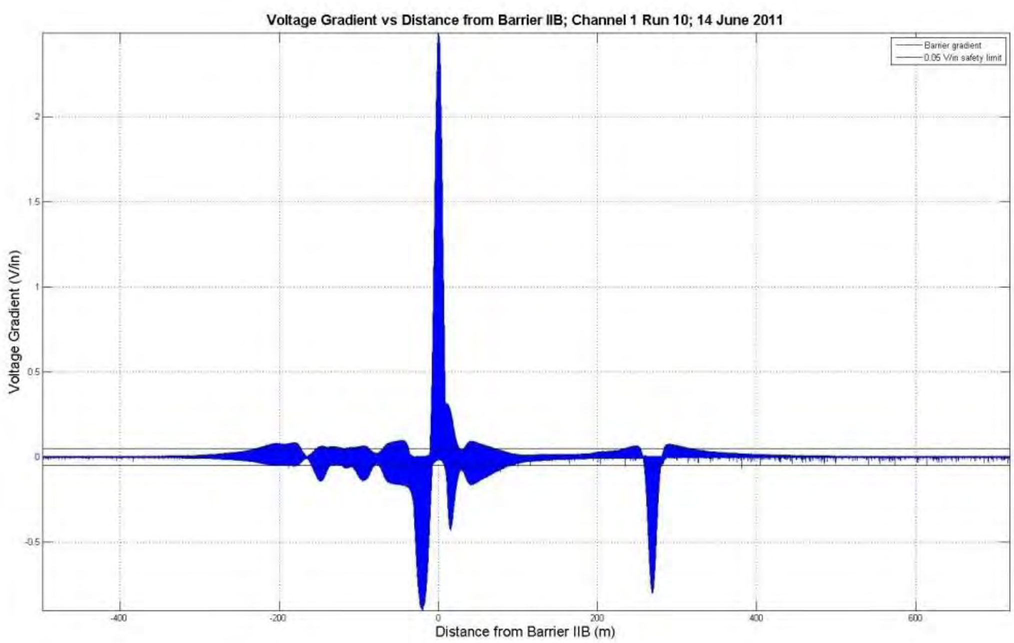

Figure C39. V12 for Run 10 on 14 June 2011 (Configuration E, On Off, On, West Wall).

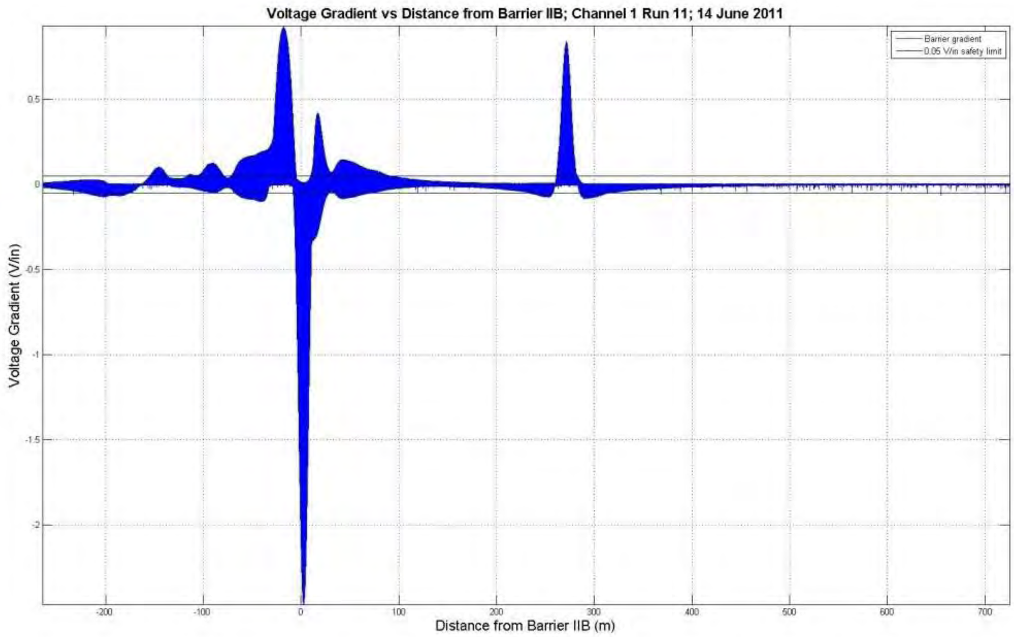

Figure C40. V12 for Run 11 on 14 June 2011 (Configuration E, On Off, On, Center).

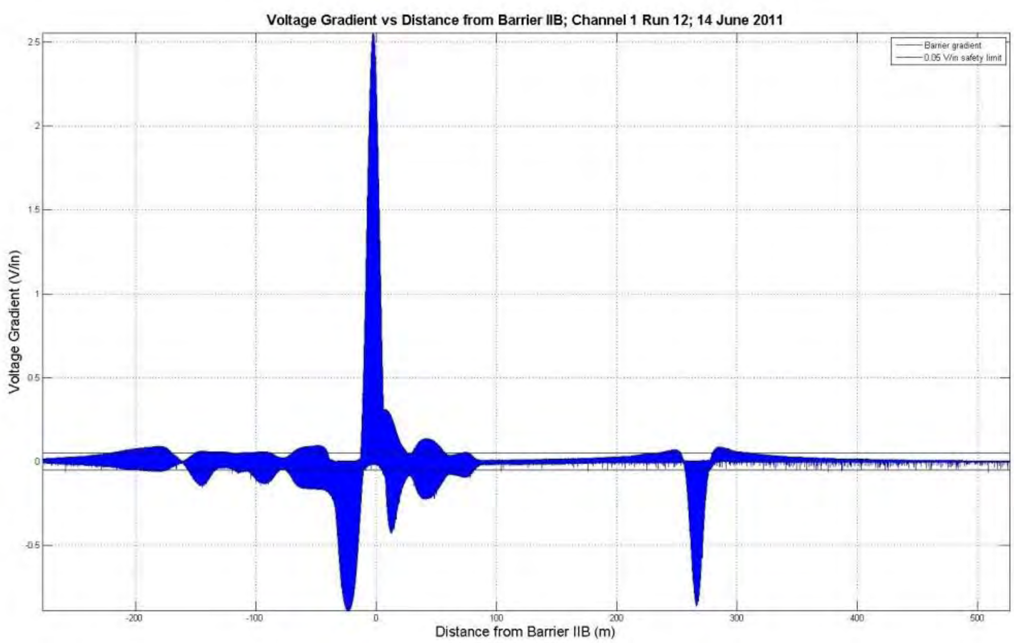

Figure C41. V12 for Run 12 on 14 June 2011 (Configuration E, On Off, On, East Wall).

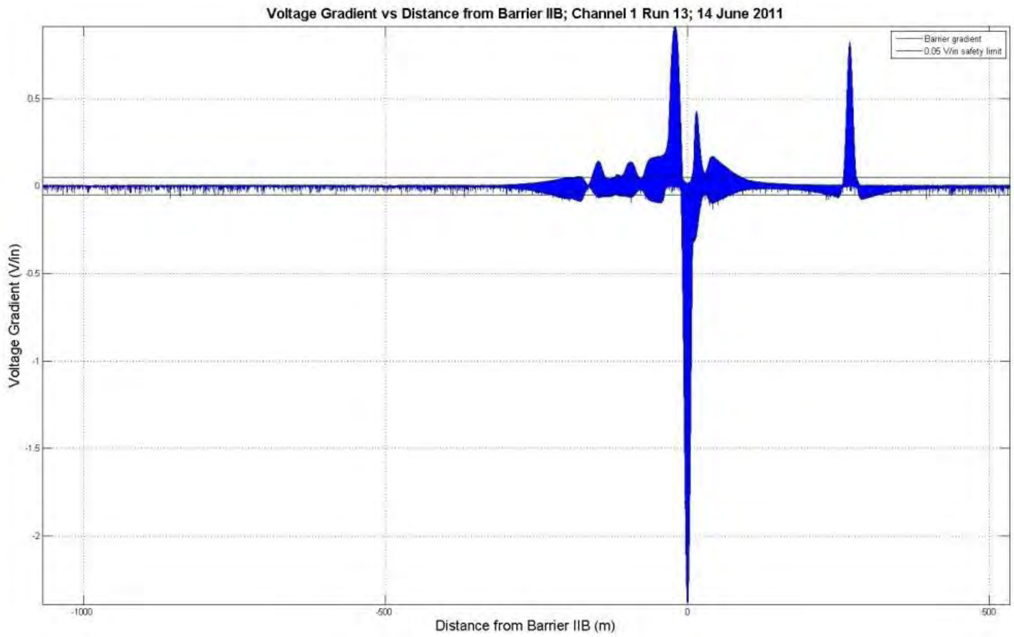

Figure C42. V12 for Run 13 on 14 June 2011 (Configuration E, On Off, On, Center).

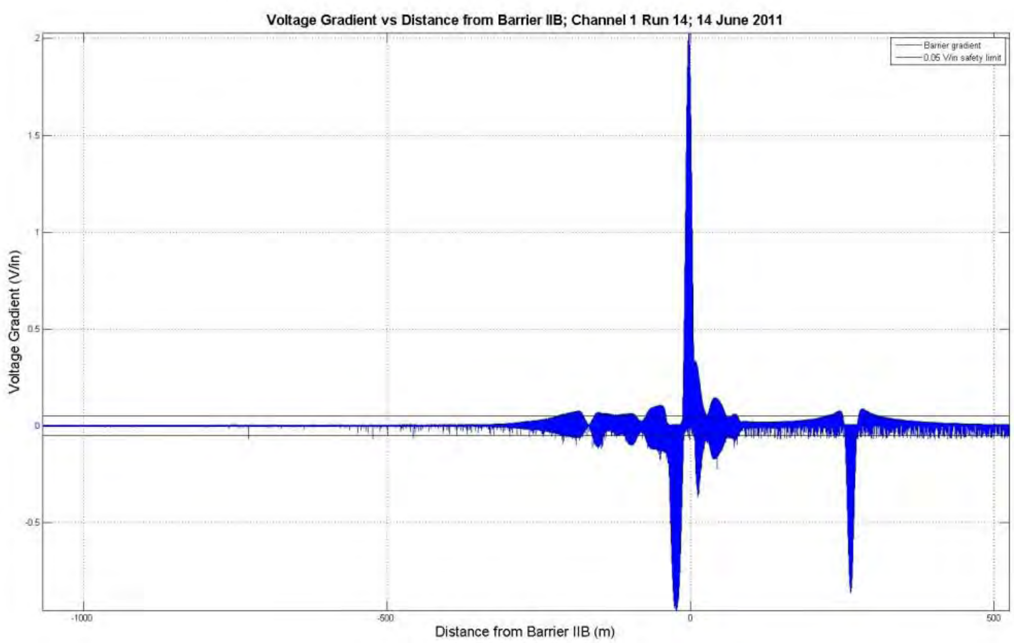

Figure C43. V12 for Run 14 on 14 June 2011 (Configuration F, On Off, On, East Wall).

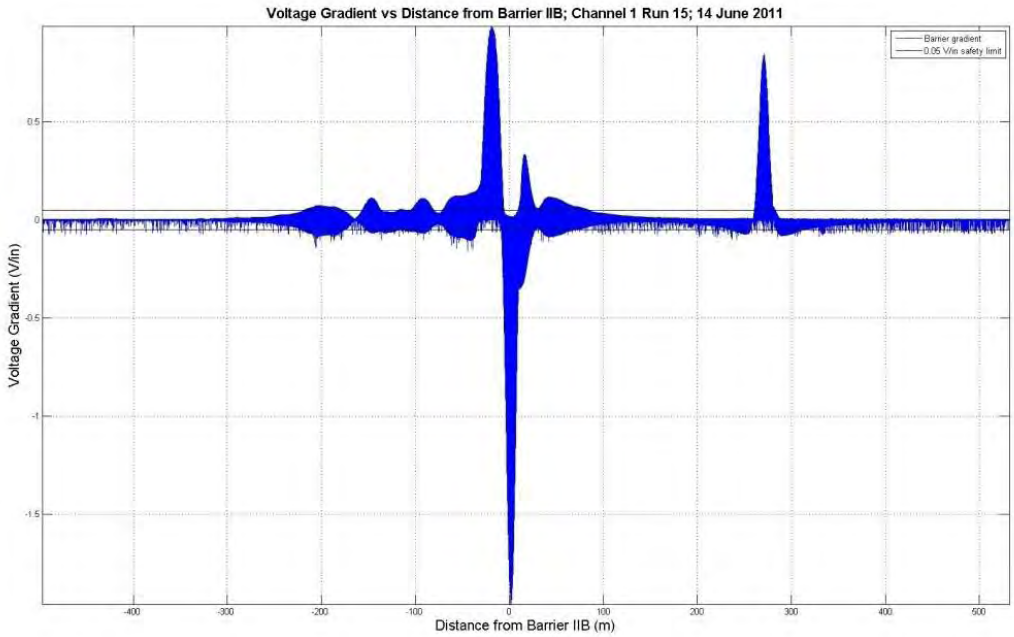

Figure C44. V12 for Run 15 on 14 June 2011 (Configuration F, On Off, On, West Wall).

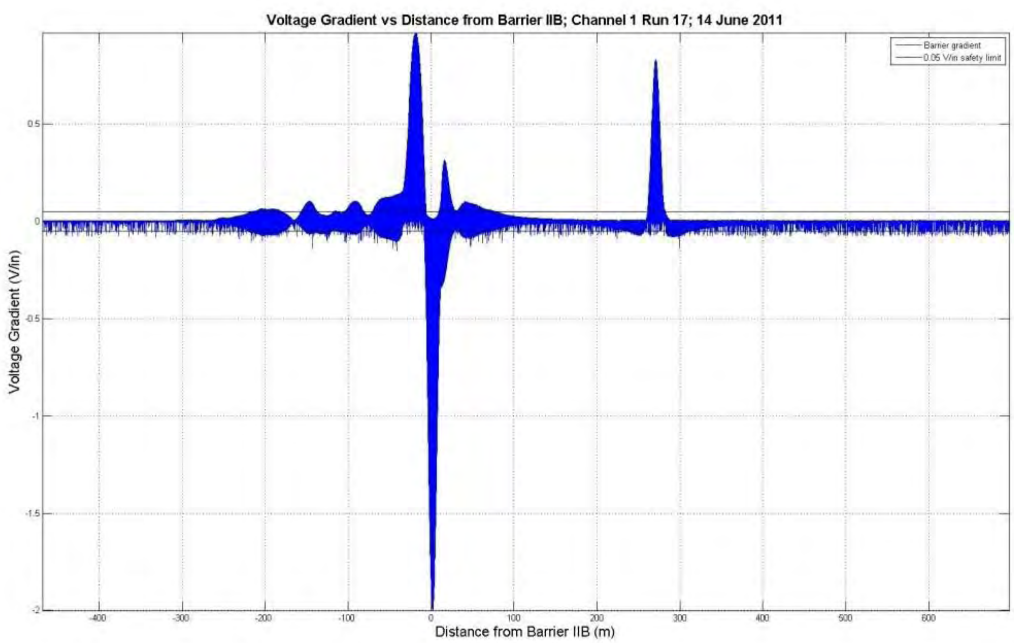

Figure C45. V12 for Run 17 on 14 June 2011 (Configuration F, On Off, On, West Wall).

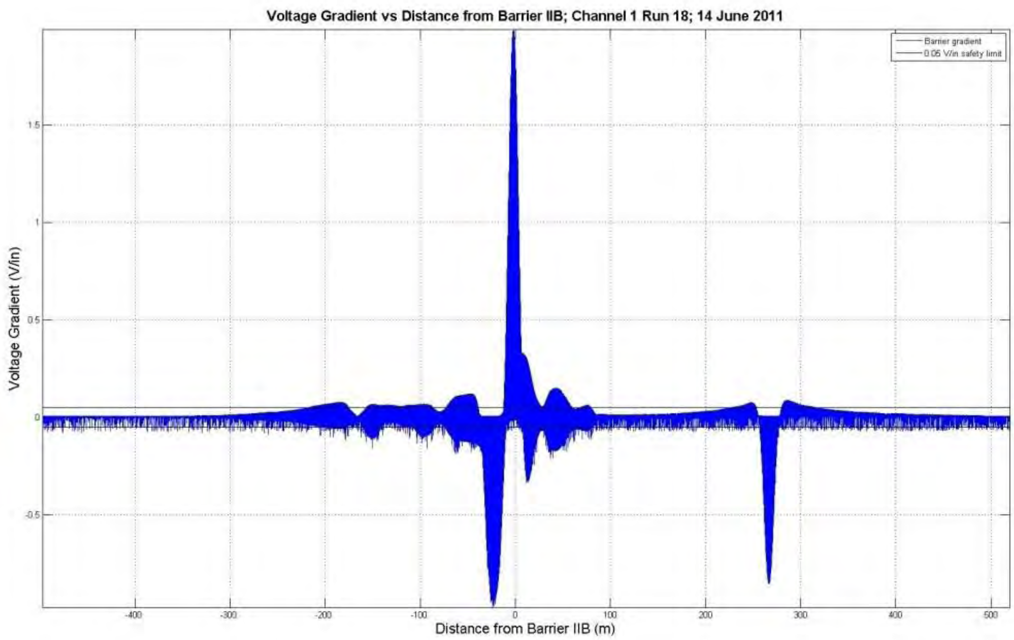

Figure C46. V12 for Run 18 on 14 June 2011 (Configuration F, On Off, On, East Wall).

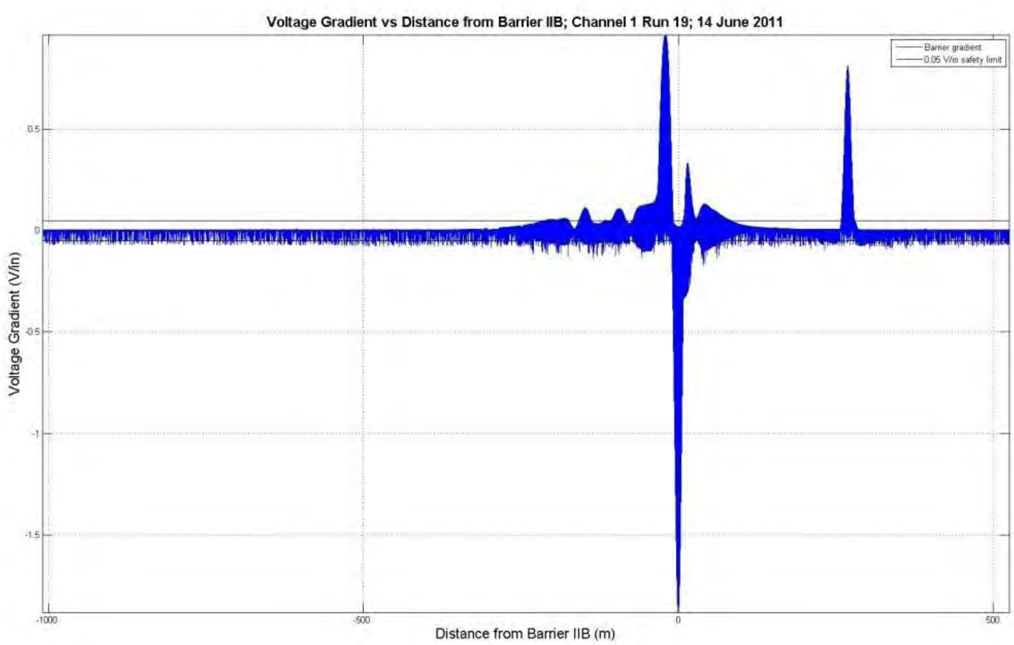

Figure C47. V12 for Run 19 on 14 June 2011 (Configuration F, On Off, On, Center).

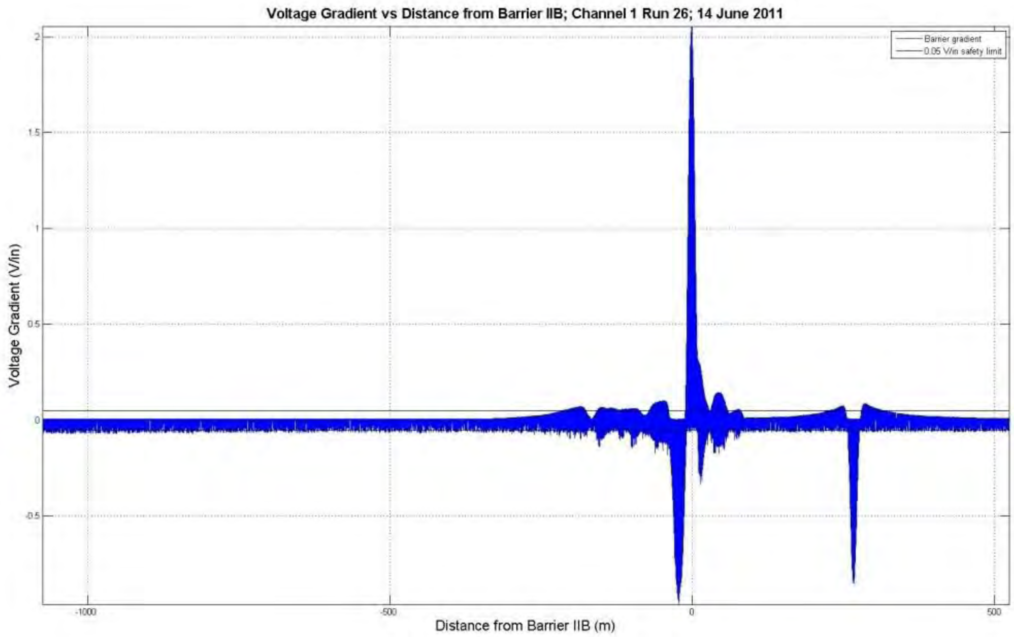

Figure C48. V12 for Run 26 on 14 June 2011 (Configuration F, On Off, On, East Wall).

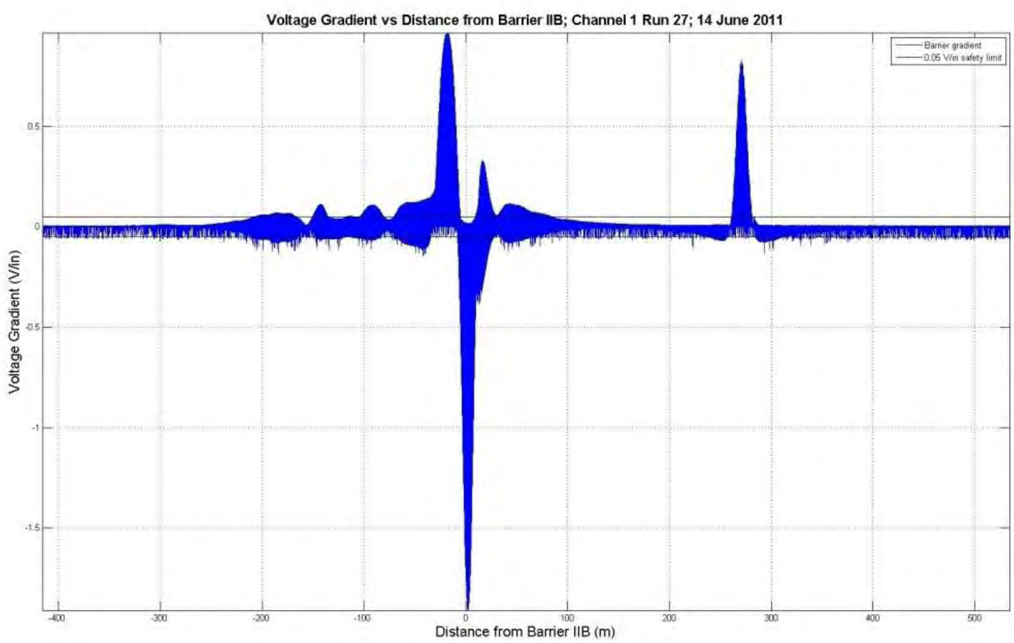

Figure C49. V12 for Run 27 on 14 June 2011 (Configuration F, On Off, On, West Wall).

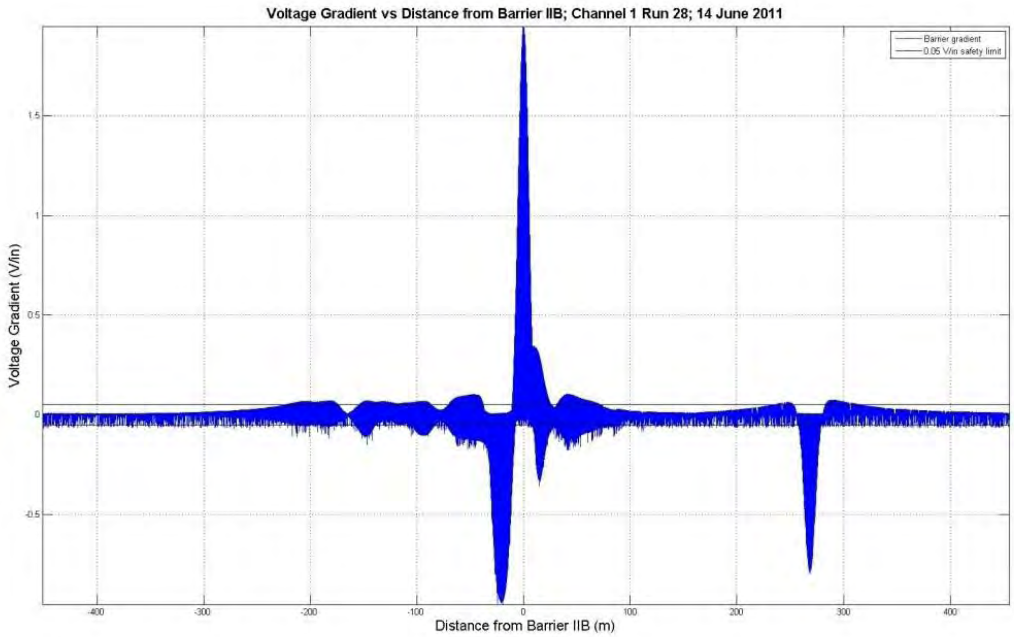

Figure C50. V12 for Run 28 on 14 June 2011 (Configuration F, On Off, On, Center).

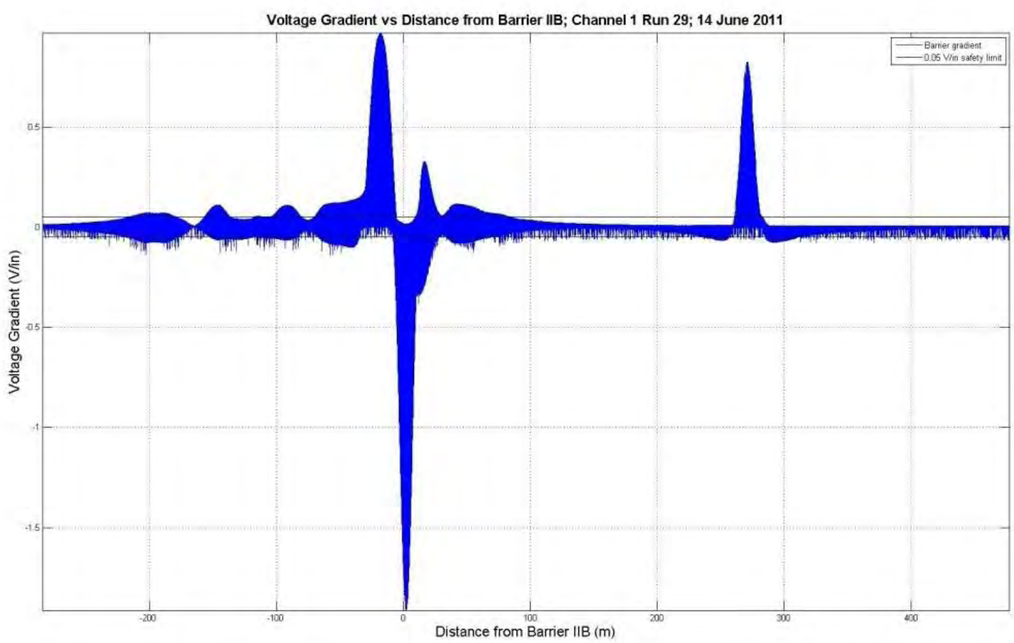

Figure C51. V12 for Run 29 on 14 June 2011 (Configuration F, On Off, On, West Wall).

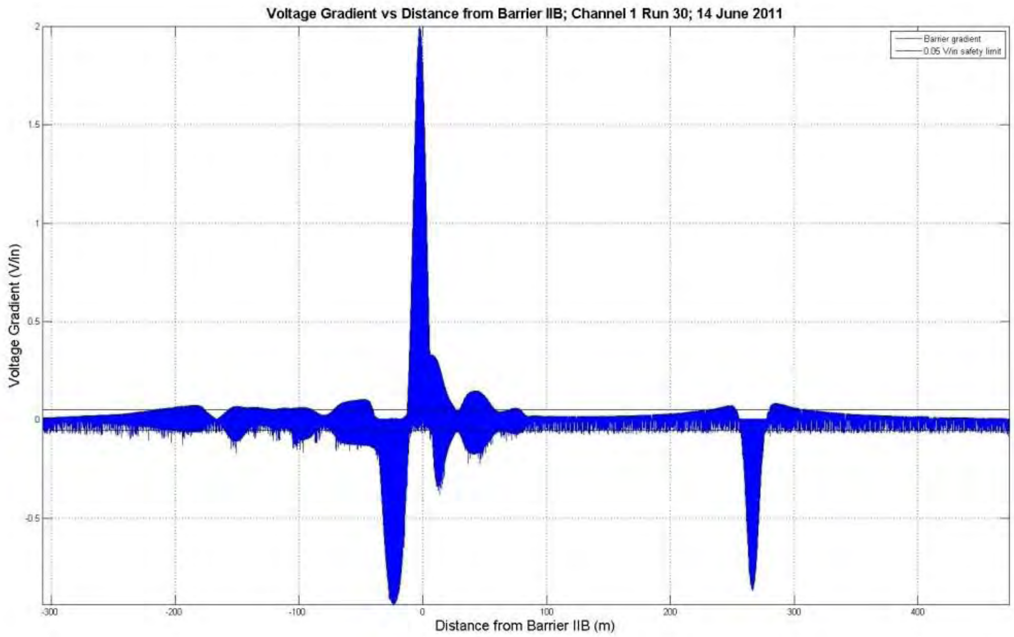

Figure C52. V12 for Run 30 on 14 June 2011 (Configuration F, On Off, On, East Wall).

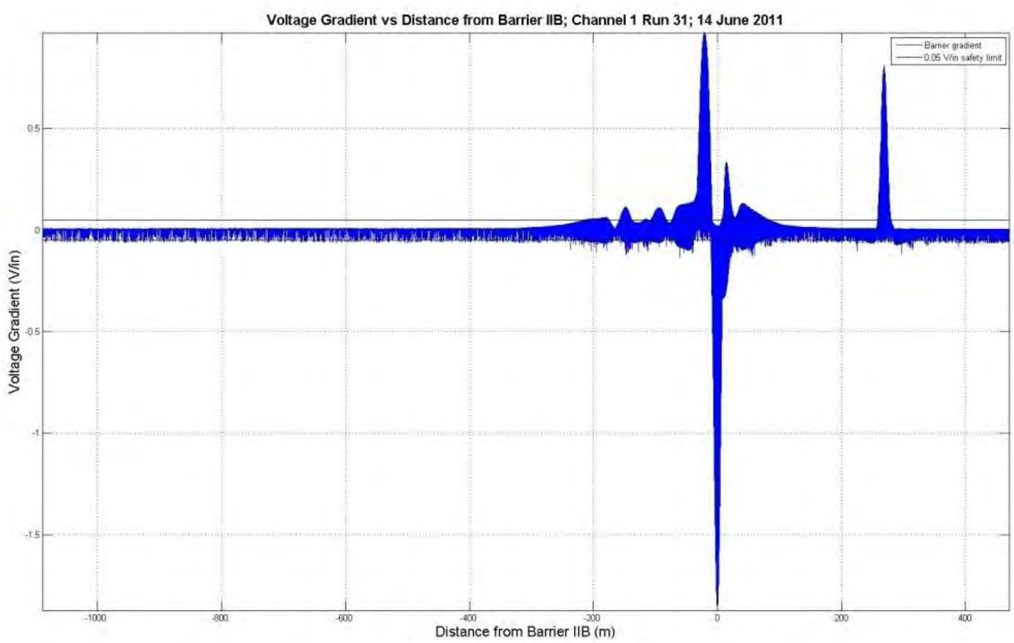

Figure C53. V12 for Run 31 on 14 June 2011 (Configuration F, On Off, On, Center).

Appendix D: V12 Electric Field Maps

This appendix contains maps of the electric field testing results for V12 (channel 1), conducted on 11 and 12 February and 14 June 2011. In these figures, the electric field strength is represented by a progressive color scale and is superimposed on a georeferenced map of the canal with key landmarks included. See Figure 2 in the body of the main report for the location of measurement V12. See Chapter 4, Table 2 in the body of the main report for details of the pulser and parasitic configurations for this data.

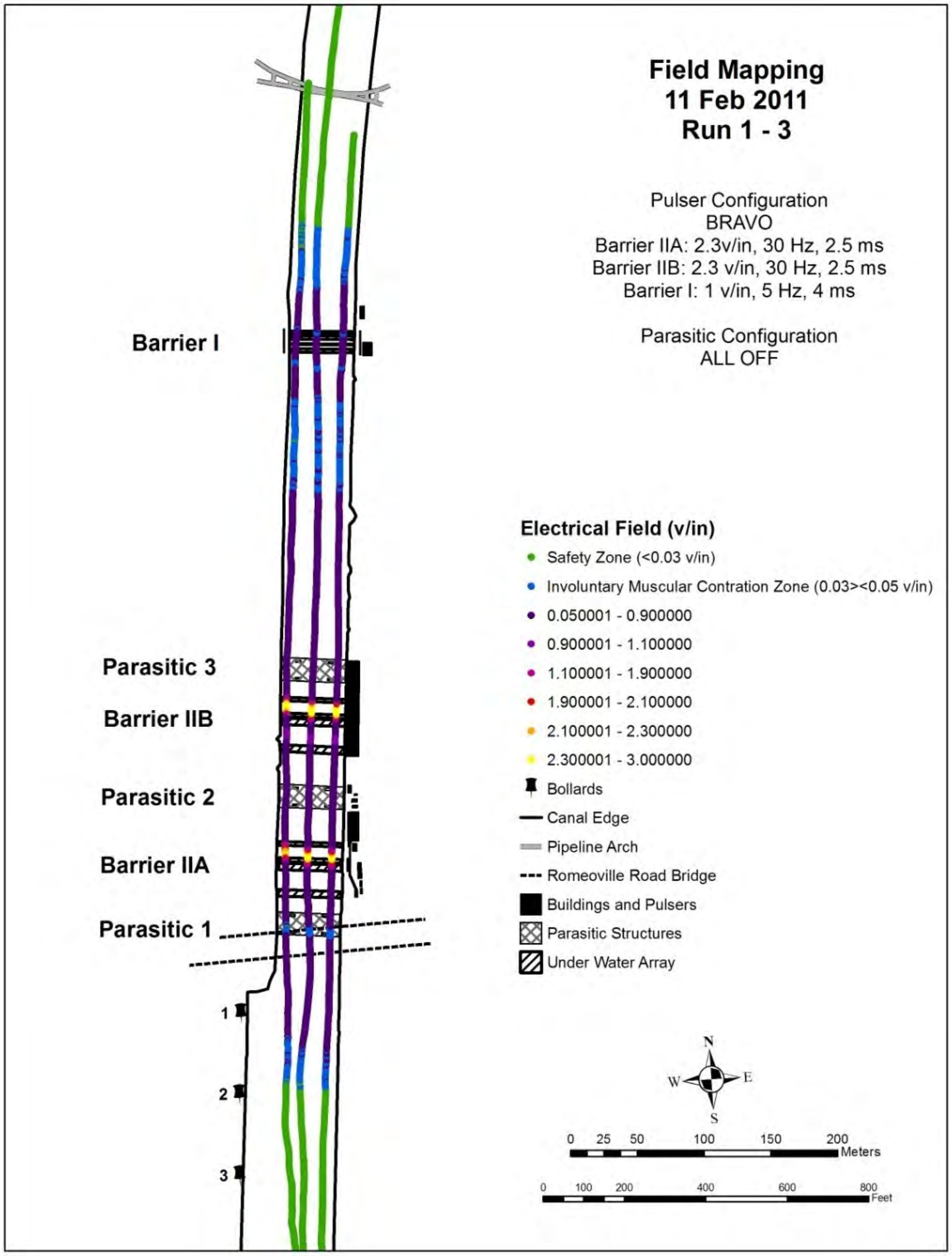

Figure D1. V12 for Runs 1 – 3 on 11 February 2011 (Configuration B, Off, Off, Off).

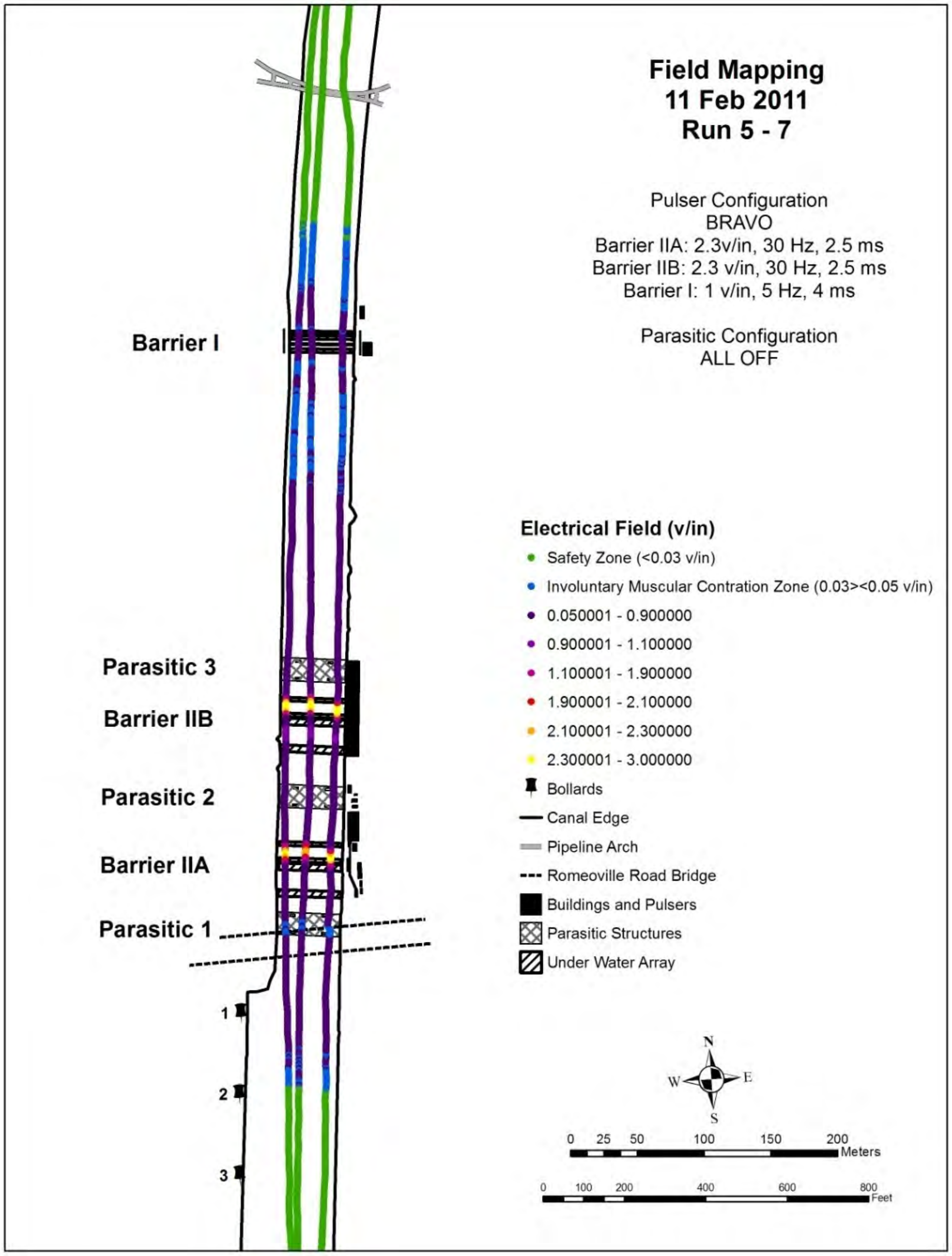

Figure D2. V12 for Runs 5 – 7 on 11 February 2011 (Configuration B, Off, Off, Off).

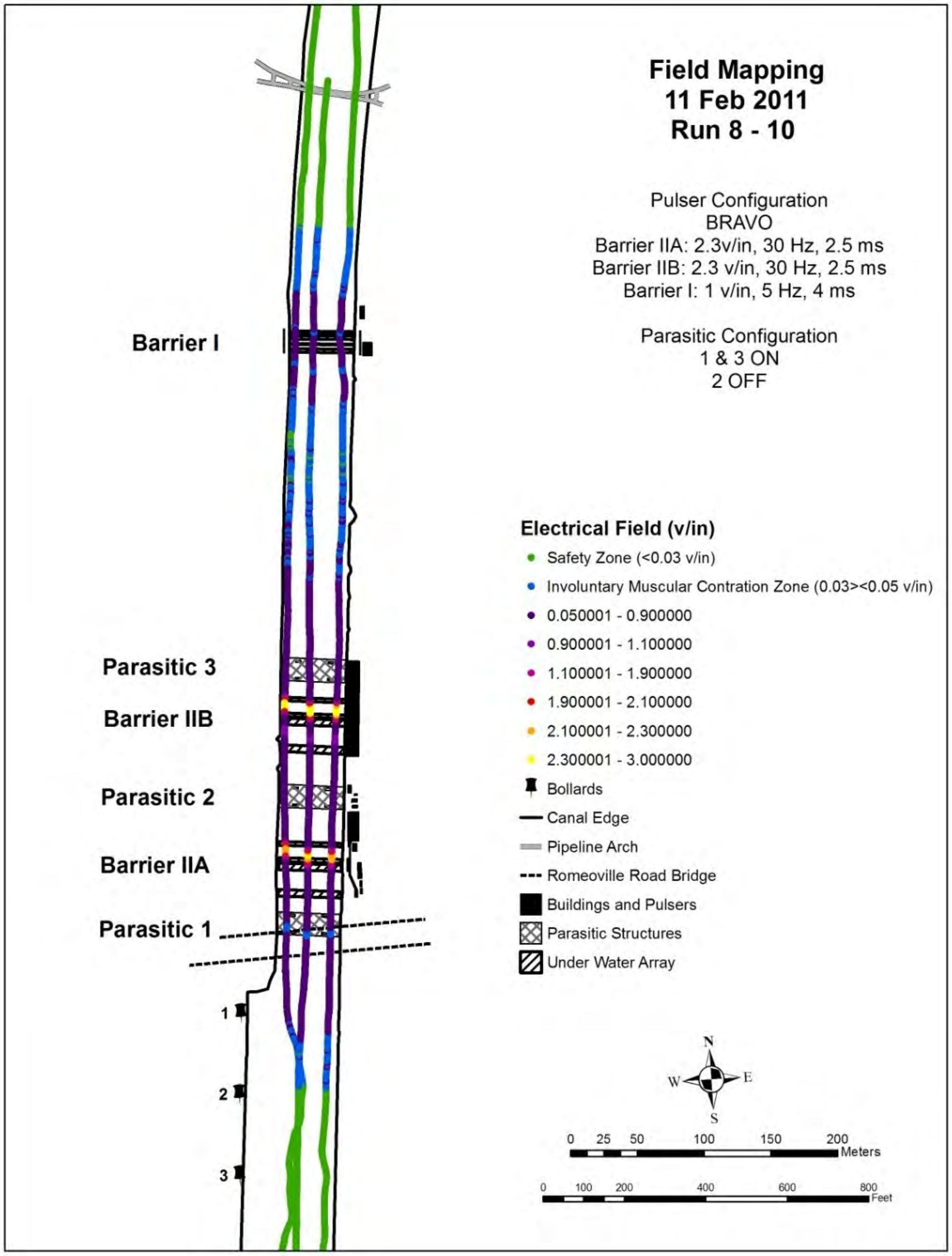

Figure D3. V12 for Runs 8 – 10 on 11 February 2011 (Configuration B, On, Off, On).

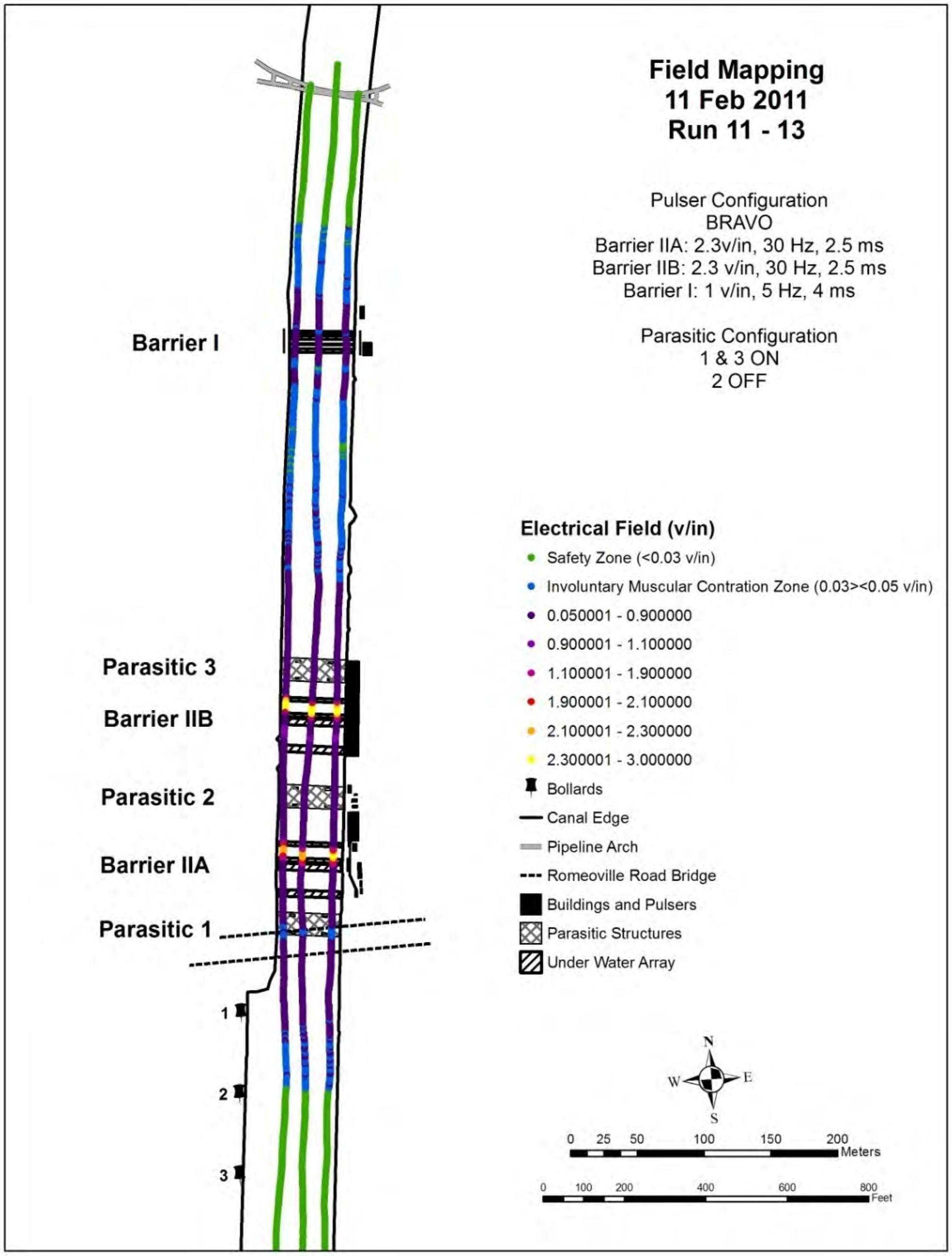

Figure D4. V12 for Runs 11 – 13 on 11 February 2011 (Configuration B, On, Off, On).

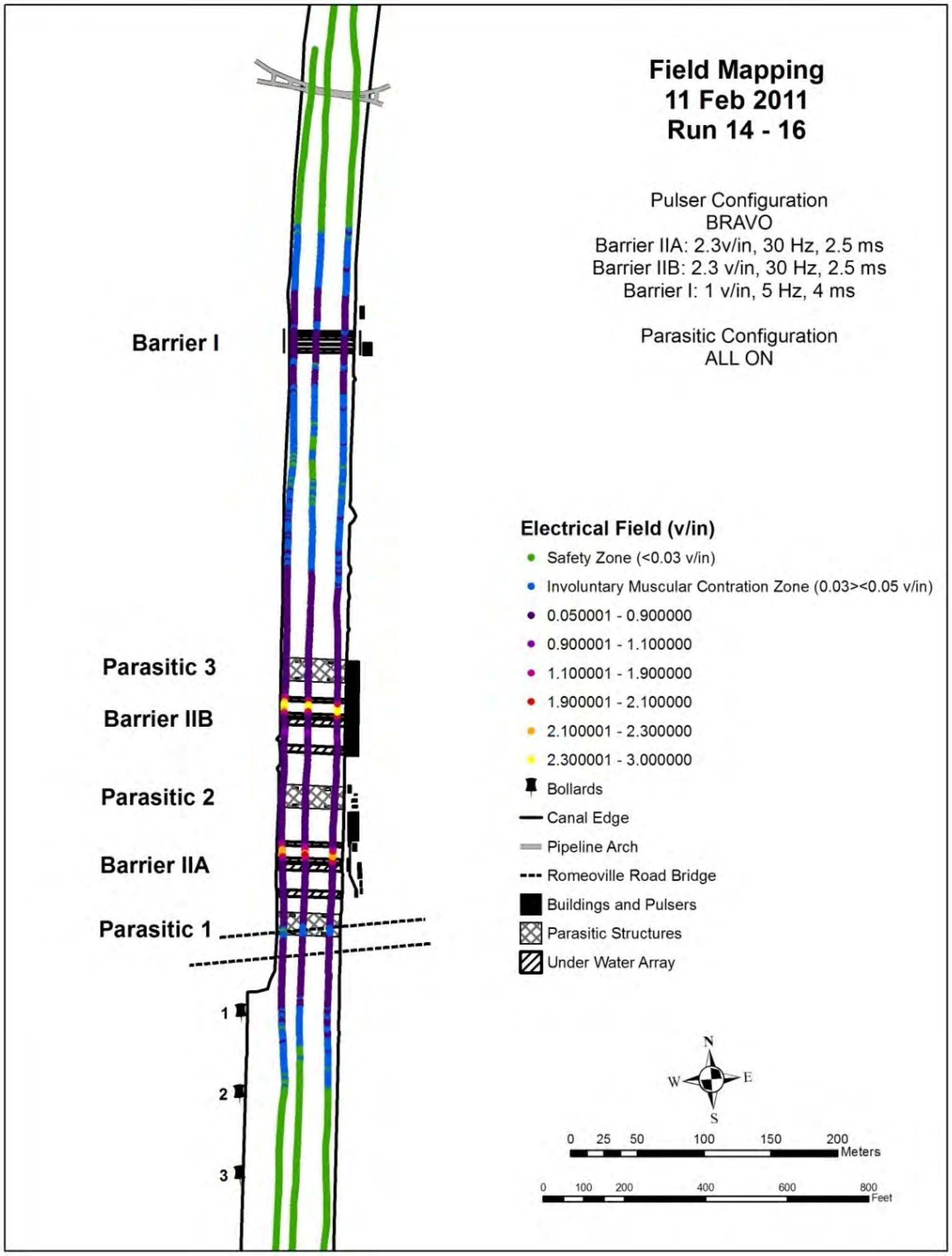

Figure D5. V12 for Runs 14 – 16 on 11 February 2011 (Configuration B, On, On, On).

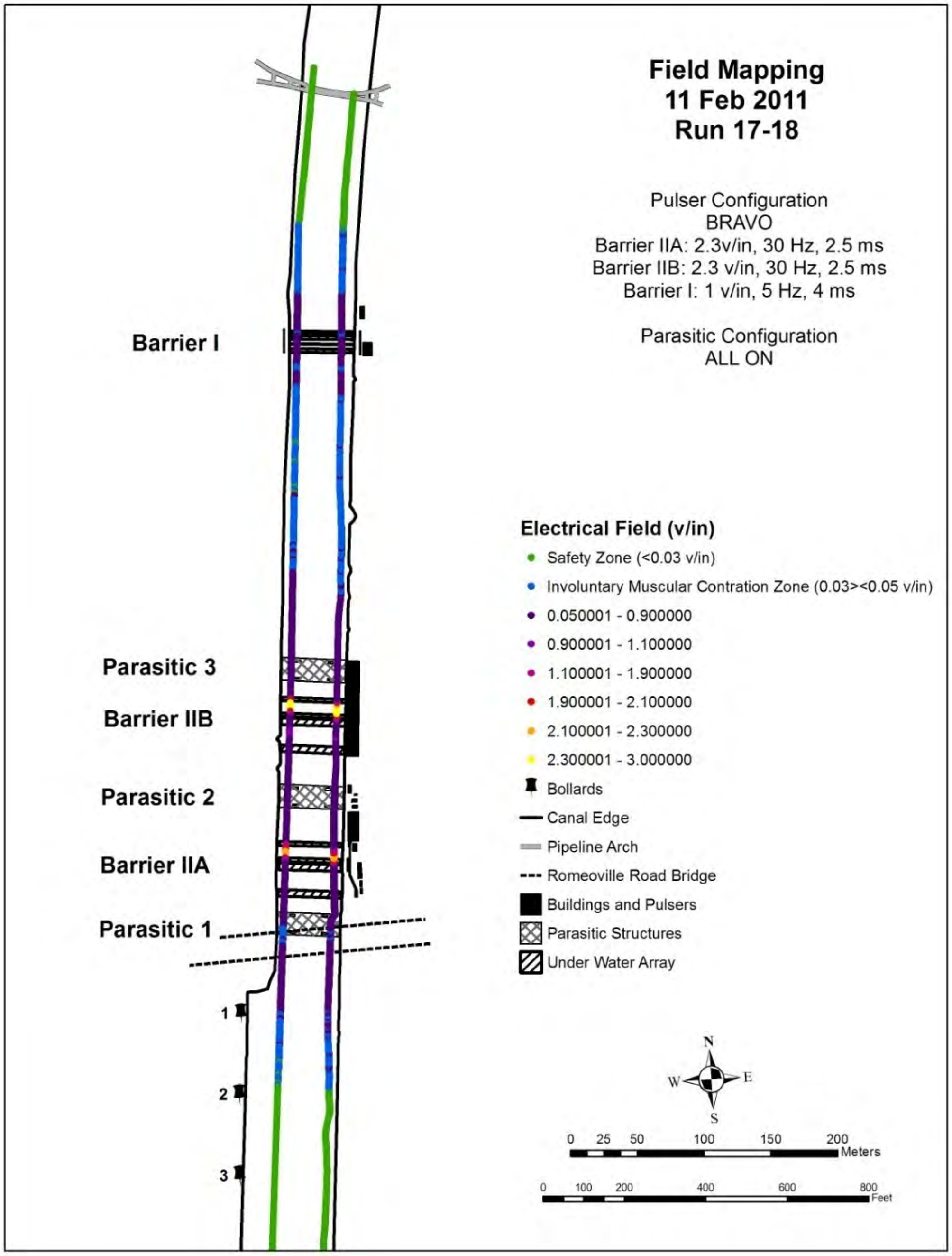

Figure D6. V12 for Runs 17 and 18 on 11 February 2011 (Configuration B, On, On, On).

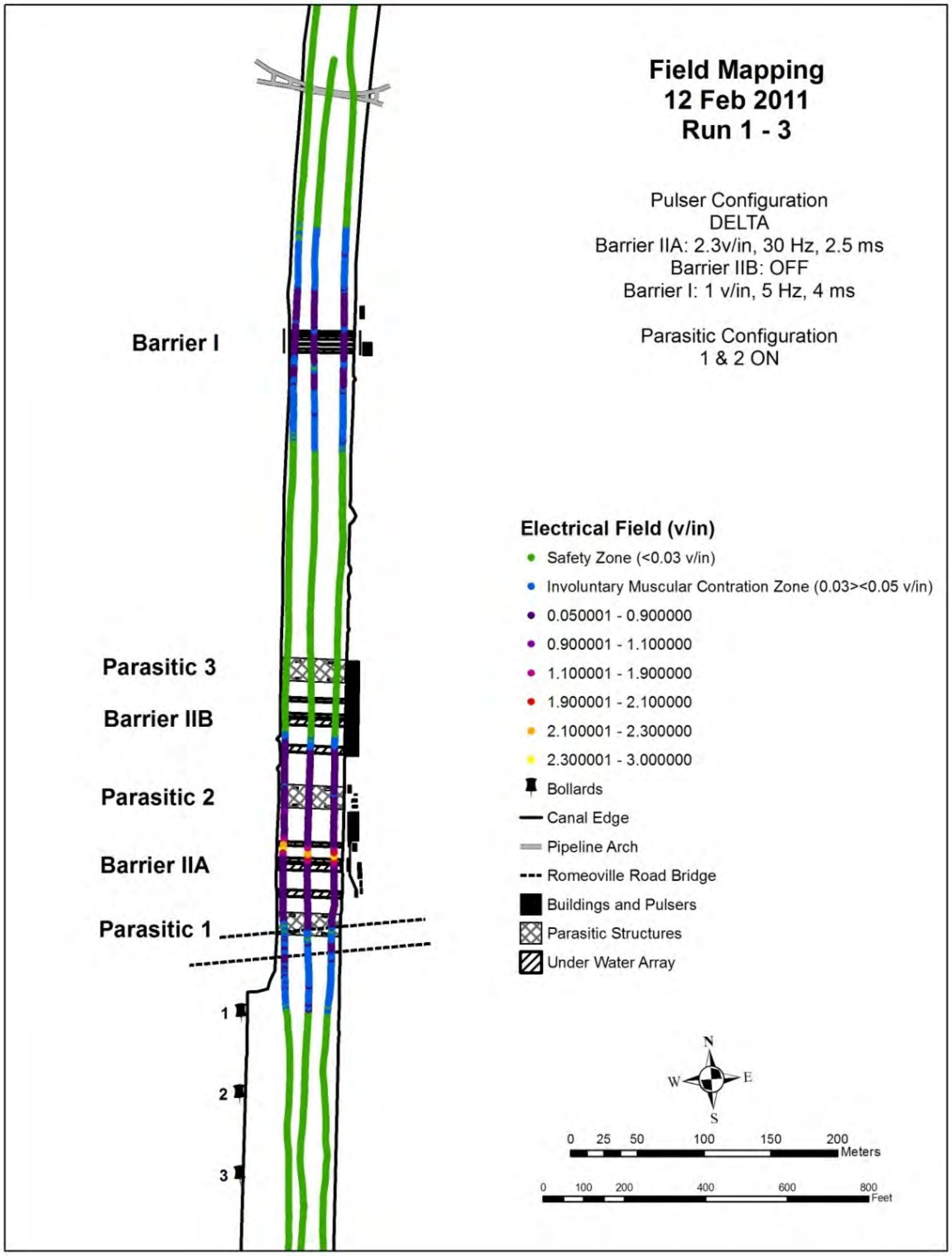

Figure D7. V12 for Runs 1 – 3 on 12 February 2011 (Configuration D, On, On, Off).

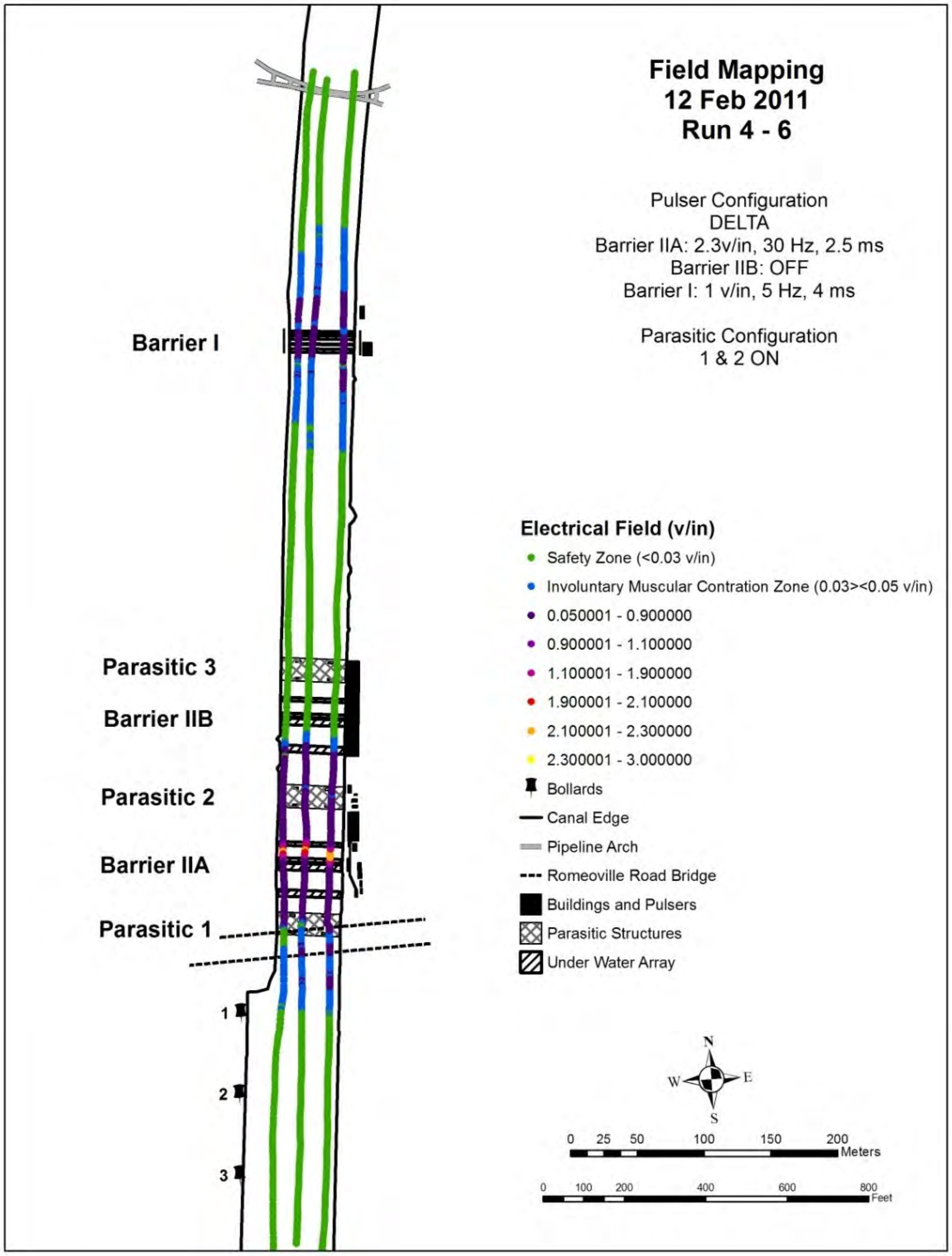

Figure D8. V12 for Runs 4 – 6 on 12 February 2011 (Configuration D, On, On, Off).

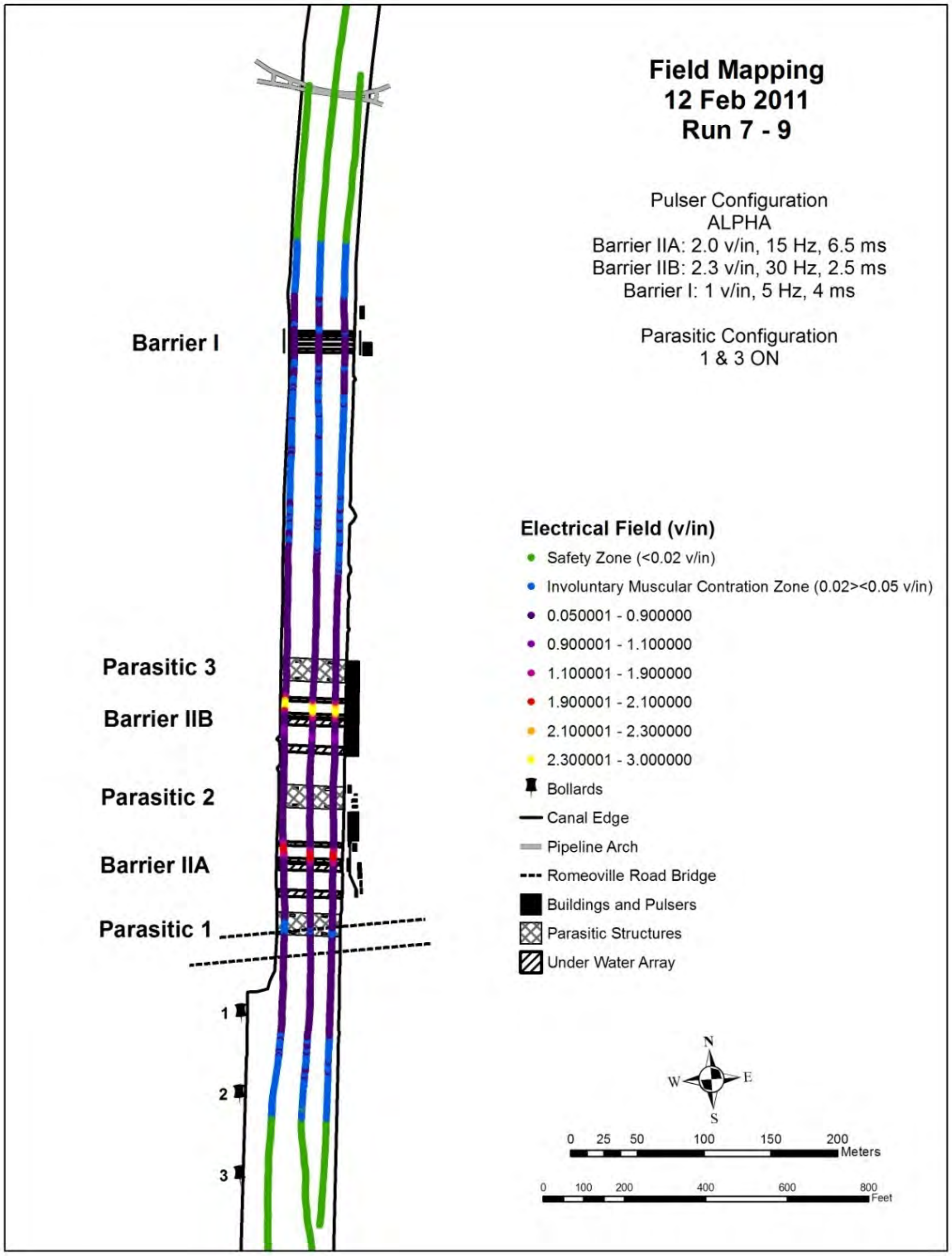

Figure D9. V12 for Runs 7 – 9 on 12 February 2011 (Configuration A, On, Off, On).

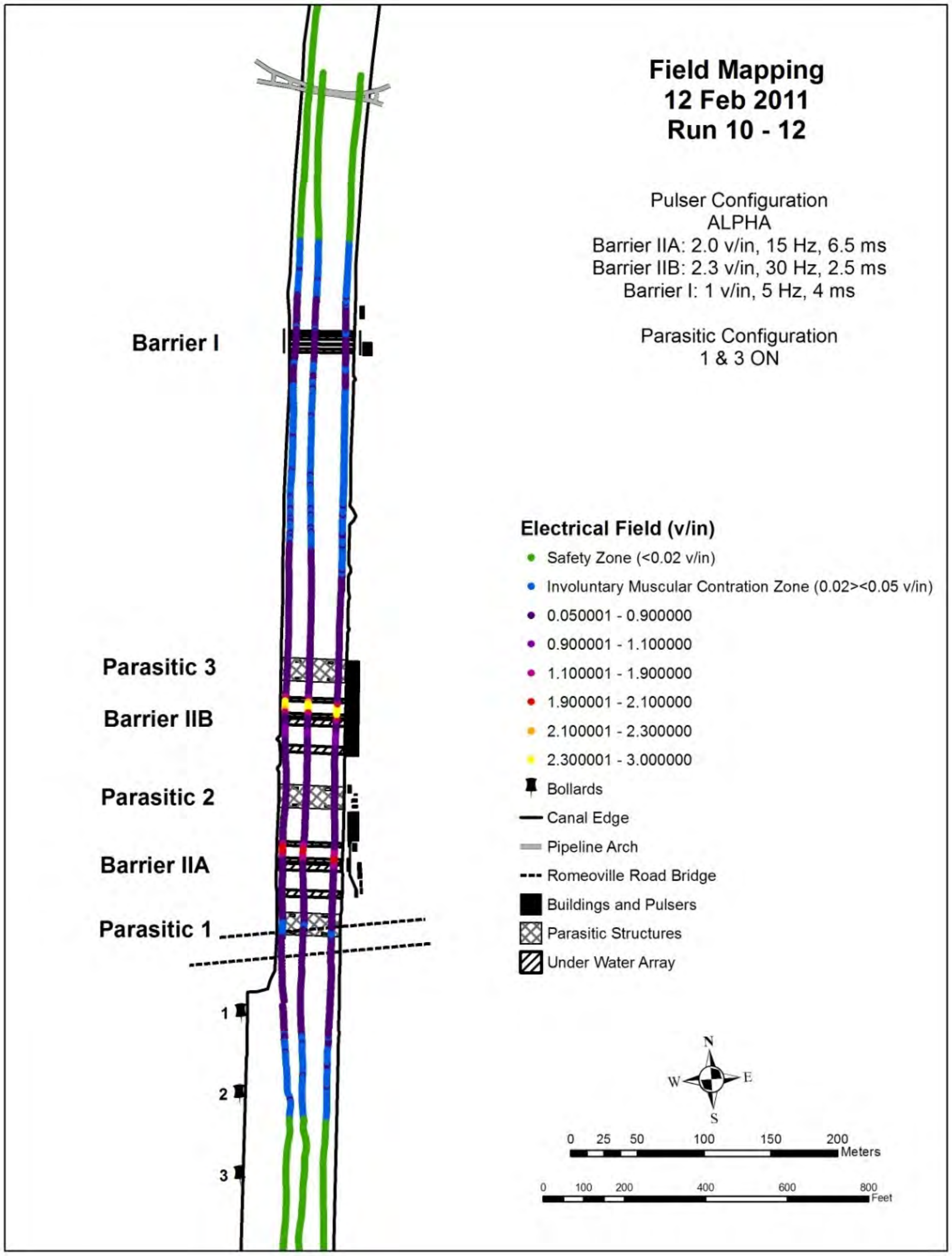

Figure D10. V12 for Runs 10 – 12 on 12 February 2011 (Configuration A, On, Off, On).

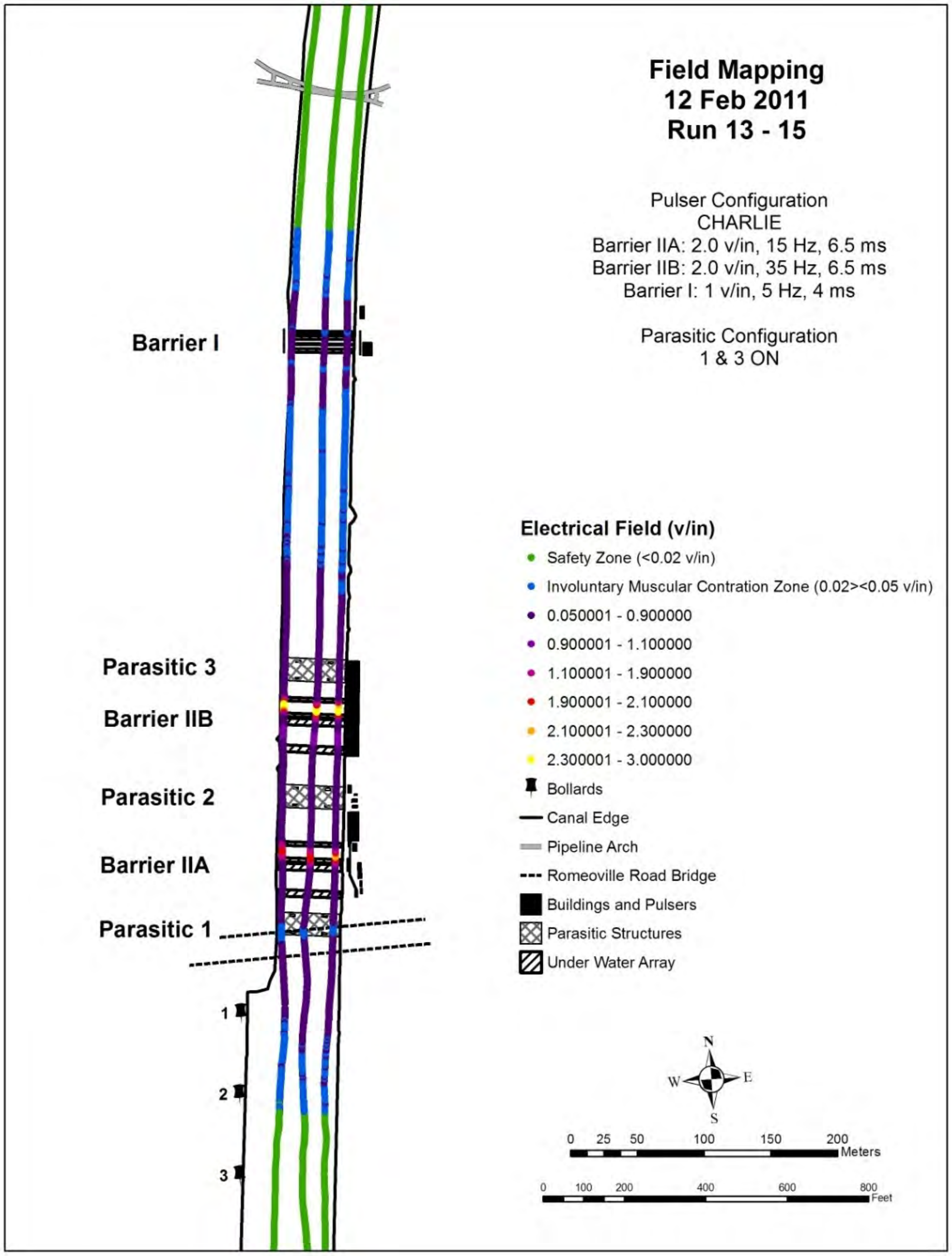

Figure D11. V12 for Runs 13 – 15 on 12 February 2011 (Configuration C, On, Off, On).

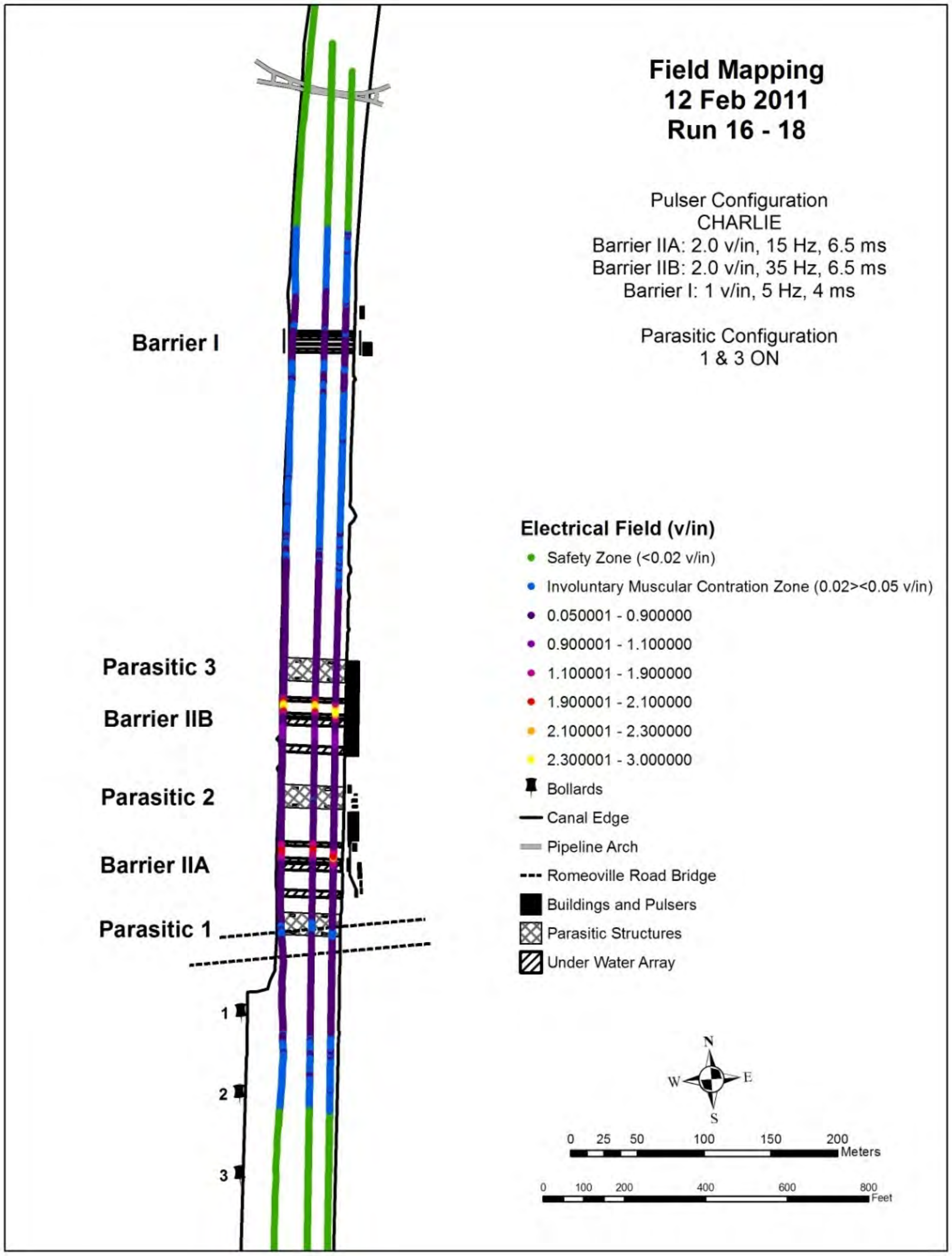

Figure D12. V12 for Runs 16 – 18 on 12 February 2011 (Configuration C, On, Off, On).

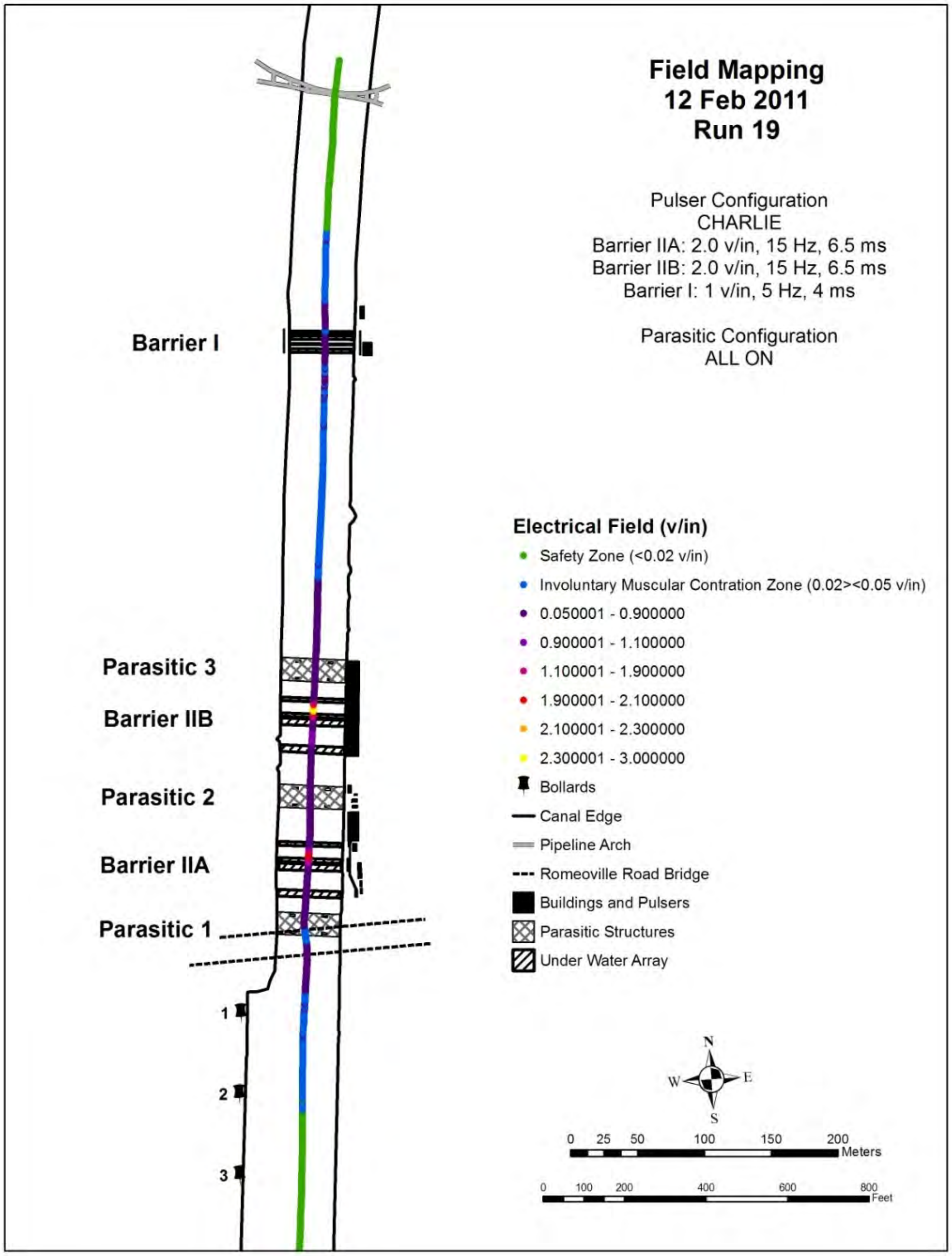

Figure D13. V12 for Run 19 on 12 February 2011 (Configuration C, On, On, On).

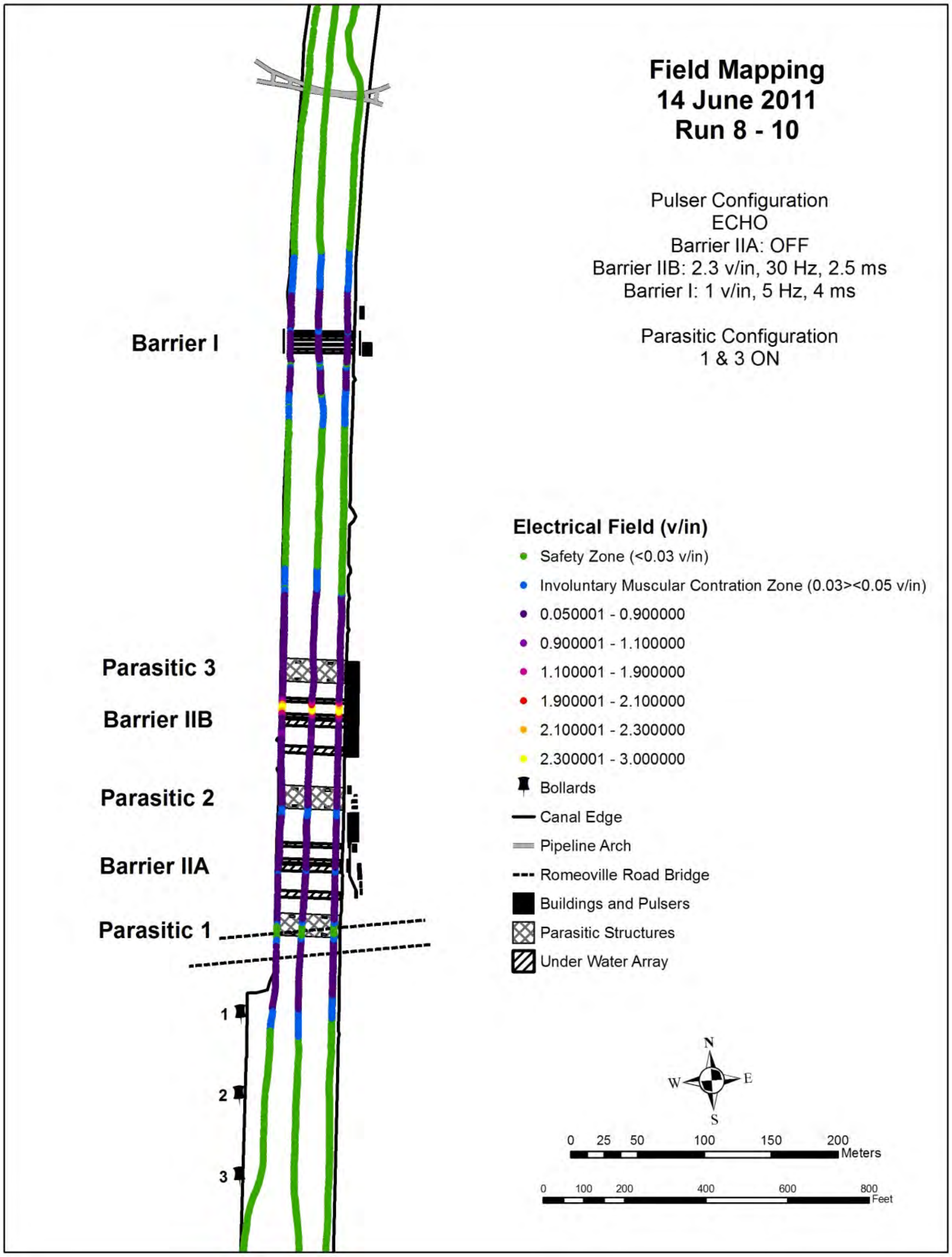

Figure D14. V12 for Runs 8 – 10 on 14 June 2011 (Configuration E, On, Off, On).

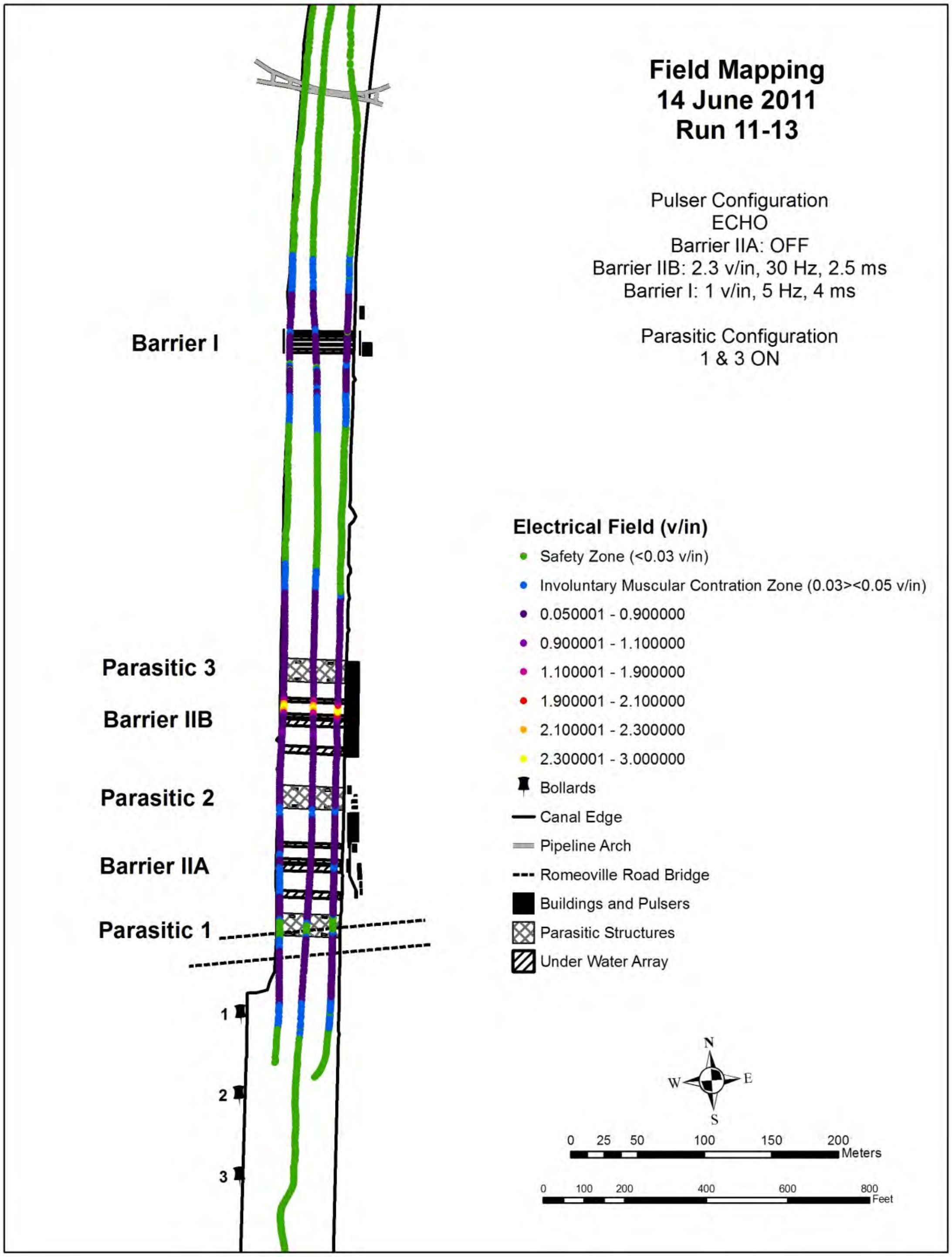

Figure D15. V12 for Runs 11 – 13 on 14 June 2011 (Configuration E, On, Off, On).

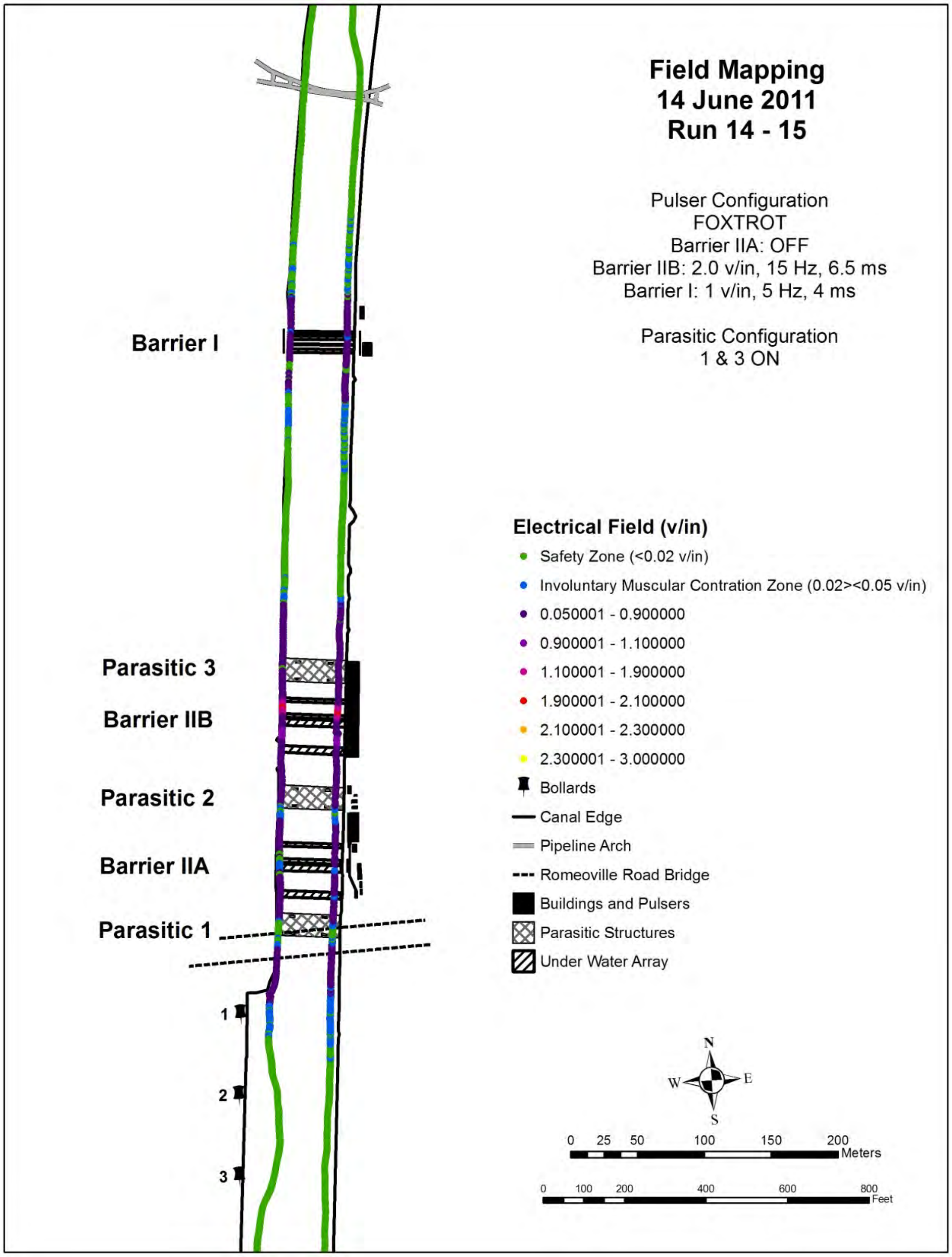

Figure D16. V12 for Runs 14 – 15 on 14 June 2011 (Configuration F, On, Off, On).

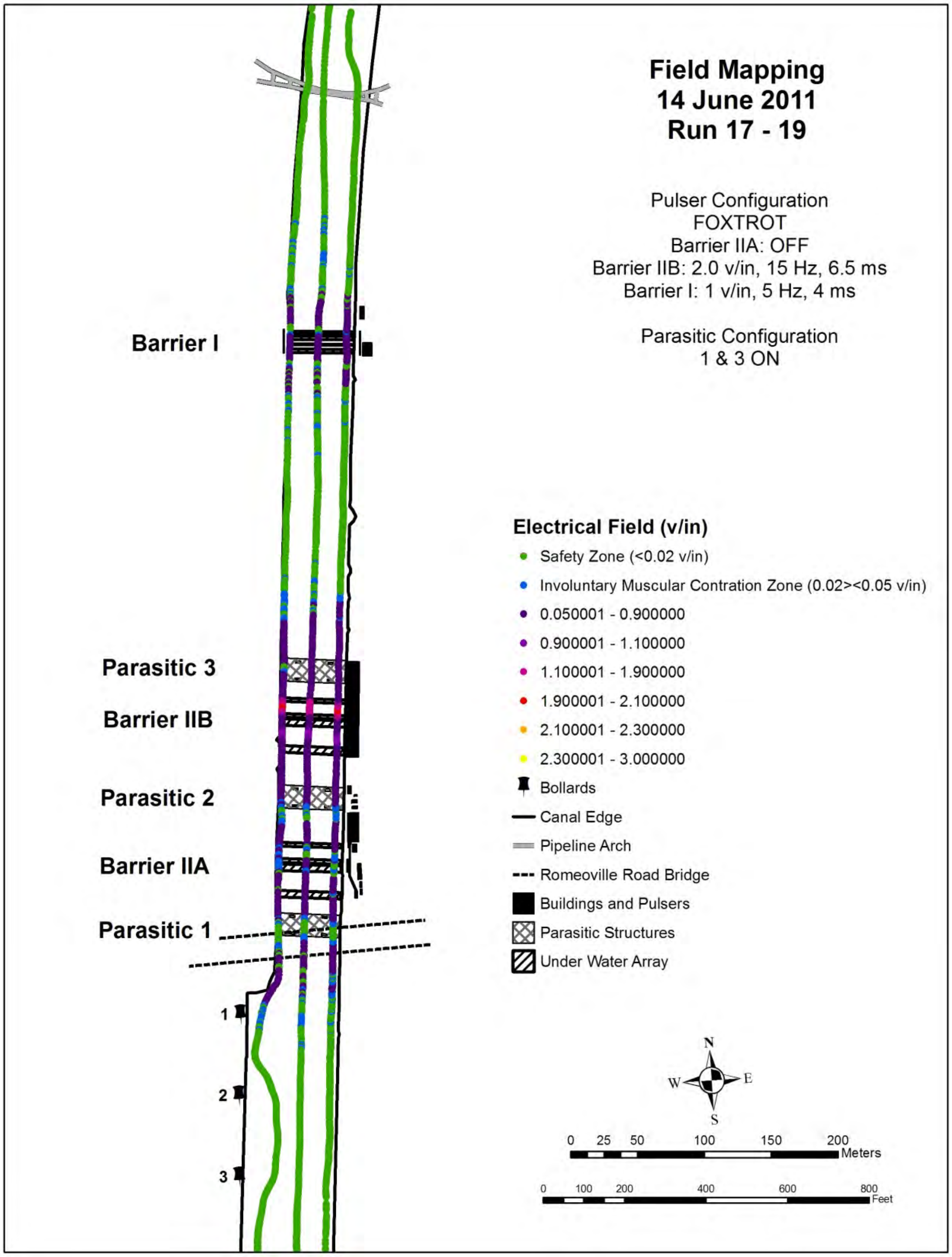

Figure D17. V12 for Runs 17 – 19 on 14 June 2011 (Configuration F, On, Off, On).

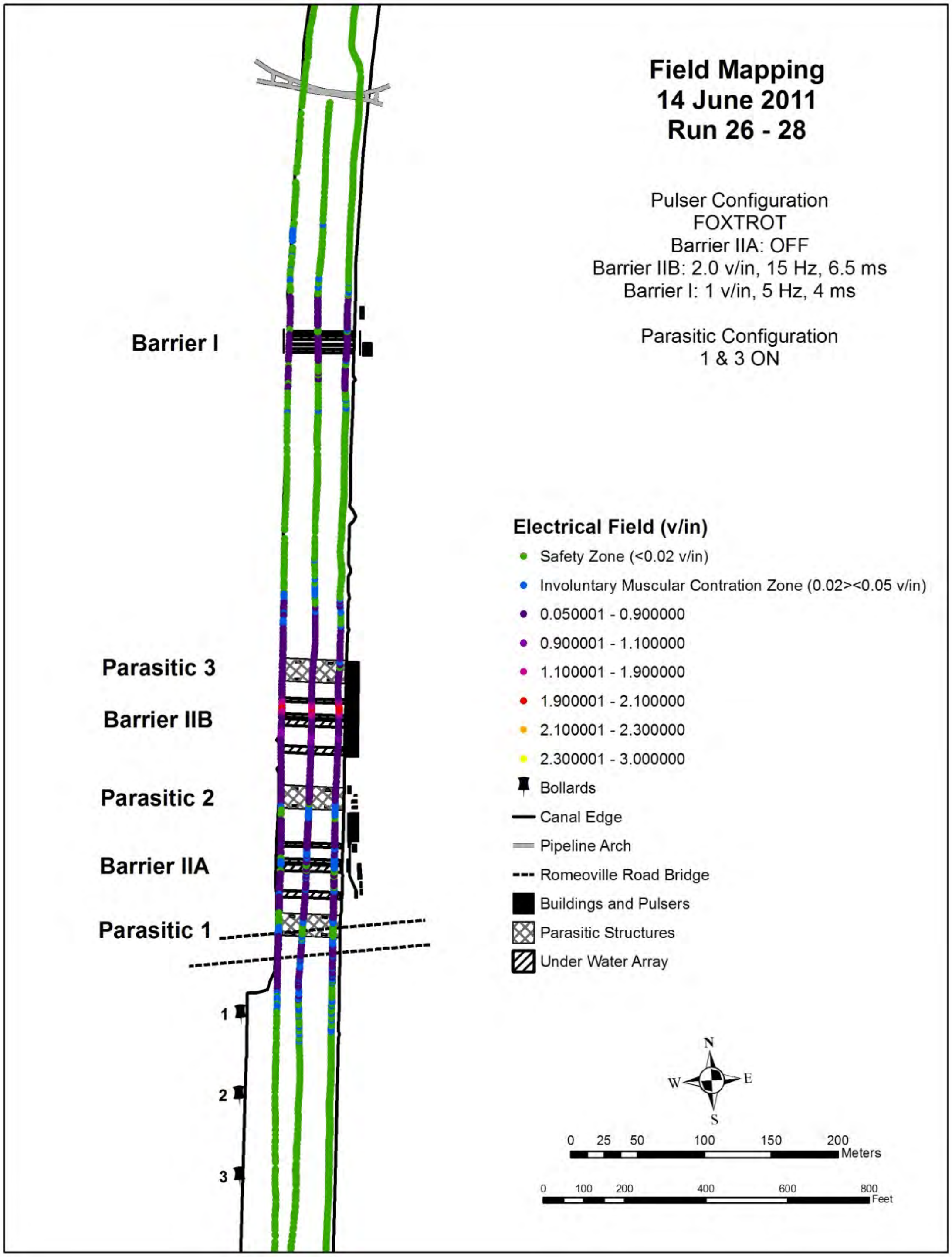

Figure D18. V12 for Runs 26 – 28 on 14 June 2011 (Configuration F, On, Off, On).

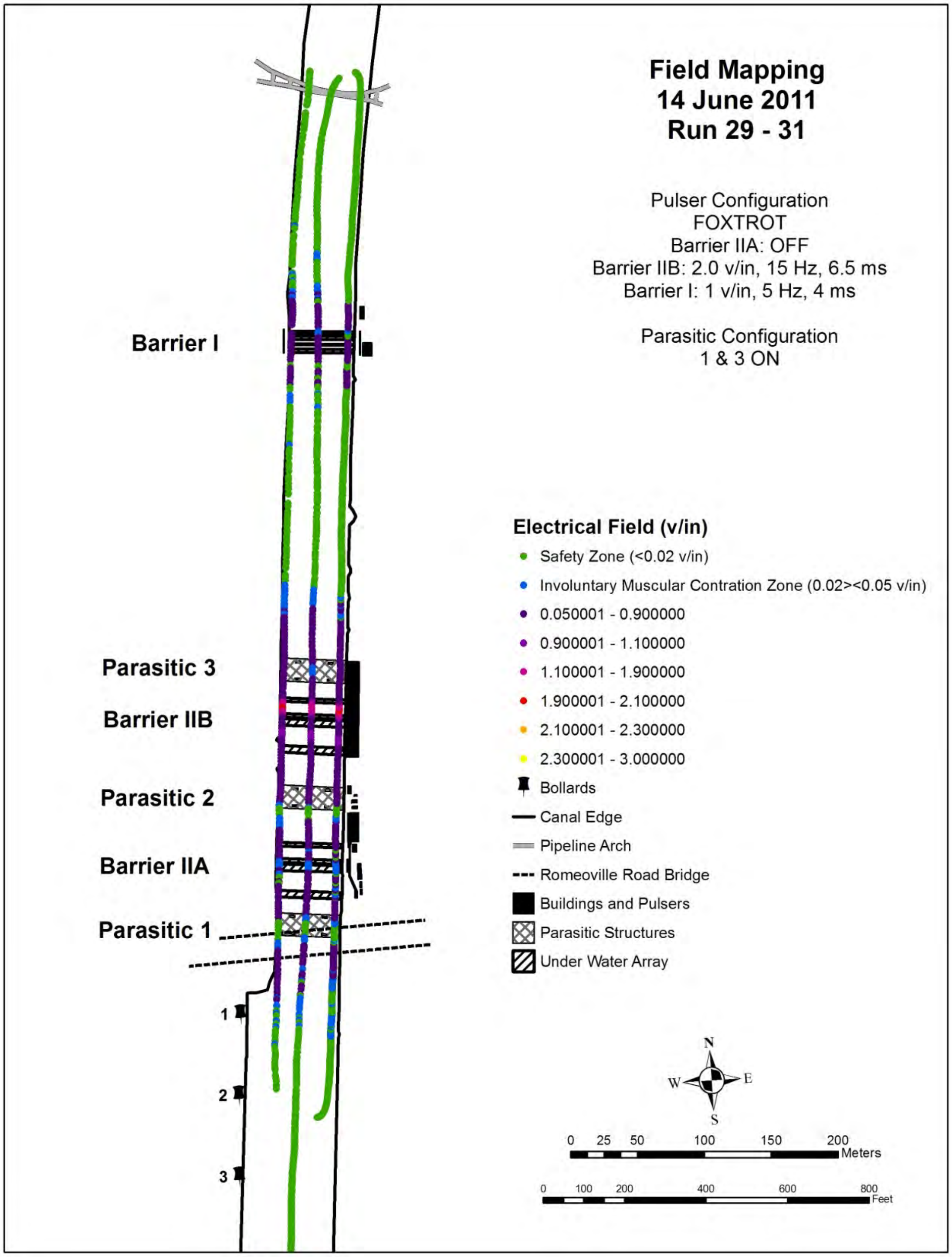

Figure D19. V12 for Runs 29 – 31on 14 June 2011 (Configuration F, On, Off, On).

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14. ABSTRACT
US Army Engineer District – Chicago operates an electric field-based aquatic nuisance species dispersal barrier system in the Chicago Sanitary and Ship Canal (CSSC), Romeoville, IL. The barriers were constructed to prevent the movement of invasive species, such as Asian bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*Hypophthalmichthys molitrix*) between the Mississippi River and Great Lakes basins. The objective of this project was to perform a series of in-water tests on the barrier addressing field-strength mapping, sparking potential during barge fleeting and collision, voltage potentials between barges traversing the barriers, personnel in-water shock potential, stray-current corrosion potential, and optimal settings for the parasitic barrier system. Test results and analysis indicate there is no significant risk of personnel shock hazard in the fleeting area during barrier operations for any operating configuration. Also, while some operational scenarios were found to increase sparking risk if barges collide with each other or separate metal objects, analysis indicates that concerns about coal dust explosion hazard from sparking are not supported by the technical literature. A detailed set of data, analysis, conclusions, and recommendations is provided in the report text and four appendices.

15. SUBJECT TERMS
Chicago Sanitary and Ship Canal (CSSC), Asian carp, fish barrier, test and evaluation, sparking potential, shock hazard

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